ABSTRACT BOOK

Scientific Organizing Committee:
P. Boumis (Greece, co-chair)
P. Slane (USA, co-chair)
T. Janka (Germany)
B-C. Koo (S. Korea)
M. Lemoine-Goumand (France)
R. Margutti (USA)
S. Orlando (Italy)
J. Raymond (USA)
S. Safi-Harb (Canada)
T. Temim (USA)
H. Yamaguchi (Japan)
P. Zhou (China)

Local Organizing Committee:
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S. Akras (Greece, co-chair)
D. Abartzi (Greece)
A. Bonanos (Greece)
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S. Derlopa (Greece)
M. Zapartas (Greece)
M. Kalitsounaki (Greece)
M. Kopsacheili (Spain)
A. Koutromanou (Greece)
I. Leonidaki (Greece)
G. Munoz-Sanchez (Greece)
D. Souropanis (Greece)
K. Tsakanika (Greece)

Venue: Minoa Palace Resort & Spa (Imperial Main Hall)

A conference organized by the National Observatory of Athens, Greece

CONFERENCE PROGRAM

Sunday June 09

16:00 – 18:30	Registration	
20:30 – 00:00	**Welcome Reception** @ beach area of Minoa Palace Resort	

Monday June 10

07:45 – 08:30	Registration	

Morning Session (Chairs: I. Leonidaki & D. Milisavljevic)

08:30 – 08:40	P. Boumis/P. Slane	Welcome
08:40 – 09:15	R. Fesen	(Opening Plenary) Recent advances in the X-Ray, radio, and optical regimes for the detection and study of Galactic and extragalactic SNRs

Session 1: Populations/Surveys and Classifications of SNRs & SNe

09:15 – 09:50	<u>M. Sasaki</u>	SNR population in nearby galaxies
09:50 – 10:10	M. Filipovic	The future is here! Diprotodon's, Potoroo's, Kyklos, ORC's and other new SNR wonders of radio surveys.
10:10 – 10:30	L. Jing	Discovery of ~2200 new SNRs in 19 nearby star-forming galaxies using MUSE spectroscopy
10:30 – 10:50	M. Kopsacheili	New larger sample of SNRs in NGC 7793, using MUSE IFS
10:50 – 11:00	1slide/1min	10 Poster Presentations - Session 1
11:00 – 11:30	**Coffee Break & Poster Viewing**	
11:30 – 12:05	<u>Y.-H. Chu</u>	Environmental effects on the LMC SNR population
12:05 – 12:25	F. Zangrandi	eROSITA study of the LMC SNRs
12:25 – 12:45	C. Treyturik	The Many Faces of Type Ia SNRs: what can X-ray observations tell us about their progenitors and explosion mechanism?
12:45 – 13:05	S. Loru	The MeerKAT view on Galactic SNRs
13:05 – 14:30	**Lunch**	

Afternoon Session (Chairs: T. Temim & N. Smith)

14:30 – 14:50	A. Rest	Light echoes of an unknown SNR in 30 Doradus

Session 2: SNe and SNRs with Circumstellar Interactions

14:50 – 15:25	P. Chandra	Unveiling the progenitors of young supernova via their circumstellar interaction
15:25 – 15:45	E. Beasor	A JWST view of the failed SN candidate N6946-BH1
15:45 – 16:05	A. Pazhayath Ravi	Latest evolution of the X-Ray remnant of SN 1987A: beyond the inner ring
16:05 – 16:20	1slide/1min	15 Poster Presentations - Sessions 1 & 2
16:20 – 16:50	**Coffee Break & Poster Viewing**	
16:50 – 17:10	S. Derlopa	SNR IC443 - morphology and kinematics of the ”Jellyfish nebula” in three dimensions
17:10 – 17:30	Y. Inoue	Toward understanding the progenitor channels to SNe Ibn/Icn: X-ray modeling of their SN-CSM interaction
17:30 – 17:50	R. Chornock	Multiwavelength observations of old stripped-envelope Supernovae
17:50 – 18:10	M. Shrestha	Polarization signature showing an elevated and asymmetric mass loss from the progenitor of SN2023ixf prior to the explosion
18:10 – 18:30	1slide/1min	20 Poster Presentations - Sessions 2 & 3
18:30 – 19:00	**Poster Viewing**	

Tuesday June 11

Morning Session (Chairs: S. Orlando & J. Vink)

Session 2: SNe and SNRs with Circumstellar Interactions

09:00 – 09:35	A. Chiotellis	On the interaction of SNRs with their CS medium: evolution, properties and progenitors imprints
09:35 – 09:55	H. Lee	Broadband non-thermal emission as an effective probe of progenitor origins of core-collapse SNRs
09:55 – 10:15	L. Dessart	Radiative transfer models for 1-10yr-old SNe: influence of interaction power, magnetar power, and dust

Session 3: SN/SNR Progenitors, Central Engines, Explosion Models

10:15 – 10:35	J. Raymond	What will Eta Car look like in 2 thousand years?
10:35 – 10:55	G. Ferrand	Typing thermonuclear explosions from observations of young supernova remnants
10:55 – 11:00	1slide/1min	5 Poster Presentations - Session 3
11:00 – 11:30	**Coffee Break & Poster Viewing**	

11:30 – 12:05	C. Fryer	Supernova Remnants as probes of the core-collapse Supernova engine and its progenitors
12:05 – 12:25	C. Ashall	Using JWST to observe supernovae from days to years past explosion
12:25 – 12:45	A. Chrimes	New insights into the Galactic magnetar population
12:45 – 13:05	M. Miceli	Collimated Fe-rich ejecta in the magnetar-hosting supernova remnant Kes 73
13:05 – 14:30	**Lunch**	

Afternoon Session (Chairs: O. Kargaltsev & A. Bonanos)

14:30 – 15:05	N. Smith	Massive star progenitors of SNe and SN remnants with strong CSM interaction
15:05 – 15:25	M. Gabler	3D long-term evolution of CCSN: connecting explosive dynamics to electromagnetic observations
15:25 – 15:45	M. Zapartas	The population of binary companions next to stripped-envelope core-collapse supernovae
15:45 – 16:05	D. Kresse	Post-explosion hydrodynamics in 3D neutrino-driven Supernova models
16:05 – 16:20	1slide/1min	15 Poster Presentations - Session 3
16:20 – 16:50	**Coffee Break & Poster Viewing**	
16:50 – 17:10	S. Kumar	Near-infrared spectroscopy of SNe Ia at nebular phases
17:10 – 17:30	K. Antoniadis	Establishing a mass-loss rate relation for Red Supergiants

Session 4: SNR Structure, Ejecta and Evolution

17:30 – 17:50	B. Williams	XRISM mission status and observations of the LMC SNR N132D
17:50 – 18:10	T. Holland-Ashford	Measuring ejecta mass ratios in Kepler's SNR to constrain its origin
18:10 – 18:30	1slide/1min	20 Poster Presentations - Sessions 3 & 4
18:30 – 19:00	**Poster Viewing**	

Wednesday June 12

Morning Session (Chairs: R. Margutti & R. Fesen)

Session 4: SNR Structure, Ejecta and Evolution

09:00 – 09:35	D. Milisavljevic	Deciphering SNR structure and evolution

09:35 – 09:55	T. Temim	A JWST view of the Crab nebula
09:55 – 10:15	P. Plucinsky	XRISM observations of Cassiopeia A
10:15 – 10:35	S. Orlando	Interpreting JWST observations of Cassiopeia A through 3D MHD modeling
10:35 – 10:55	R. Wesson	3D mapping of the ejecta of SN1987A with ALMA
10:55 – 11:00	1slide/1min	5 Poster Presentations - Session 4
11:00 – 11:30	**Coffee Break & Poster Viewing**	
11:30 – 12:05	J. Larsson	SN 1987A in the JWST era — compact object, ejecta structure and CSM interaction

Session 5: Shock Physics, Particle Acceleration, Polarization in SNRs and PWNe

12:05 – 12:40	J. Vink	X-ray polarimetry of supernova remnants with IXPE: puzzling magnetic-field geometries and high levels of downstream turbulence
12:40 – 13:00	R. Bandiera	Synchrotron polarization with a partially random magnetic field: general theory, and applications to IXPE observations of young SNRs
13:00 – 13:20	M. Matsuura	JWST NIRCam observations of Supernova 1987A – shocks, synchrotron and dust
13:20 – 13:40	O. Petruk	Evolution of magnetic field structure in SN1987A
13:40 – 14:00	**Conference Photo**	
15:15 – 22:30	**Excursion #1: Tour to Dourakis winery & to Rethymno City**	
15:15	Buses depart from Minoa Palace Resort	
22:30	Buses arrive to Minoa Palace Resort	

Thursday June 13

Morning Session (Chairs: J. Raymond & R. Kothes)

Session 5: Shock Physics, Particle Acceleration, Polarization in SNRs and PWNe

09:00 – 09:35	N. Bucciantini	PWNe in the light of the new IXPE observations: putting our understanding to the test
09:35 – 09:55	D. Caprioli	Particle acceleration at SNR shocks: bridging simulations and observations
09:55 – 10:15	P. Ghavamian	Electron-ion equilibration and cosmic-ray acceleration in two Balmer-dominated SNRs
10:15 – 10:35	G. Morlino	Acceleration and release of electrons from SNRs
10:35 – 10:55	R. Diesing	SNRs in their golden years: predicting the bright, nonthermal signatures of radiative shocks

10:55 – 11:00	1slide/1min	5 Poster Presentations – Sessions 4 & 5
11:00 – 11:30	**Coffee Break & Poster Viewing**	
11:30 – 11:50	H. Sano	Shock-cloud interactions in Supernova Remnants revealed by ALMA

Session 6: SN/SNR dust, environments, feedback

11:50 – 12:25	<u>I. De Looze</u>	SN dust formation and destruction in the JWST era
12:25 – 12:45	M. Shahbandeh	Unraveling cosmic dust origins: JWST revelations from Supernovae
12:45 – 13:05	E. Dwek	The attenuated emission model for the late-time JWST spectrum of SN2010jl
13:05 – 14:30	**Lunch**	

Afternoon Session (Chairs: M. Lemoine-Goumand & J. Larsson)

14:30 – 15:05	<u>B.-W. Jiang</u>	The extinction distances to Supernova Remnants and the dust properties
15:05 – 15:25	F. Kirchschlager	Dust destruction by the reverse shock in clumpy supernova remnants
15:25 – 15:45	T. Szalai	Populating the gap in dust-formation history of Type II(P) Supernovae with JWST
15:45 – 16:05	A. Sarangi	Modeling dust formation in Supernovae
16:05 – 16:20	1slide/1min	15 Poster Presentations - Sessions 5 & 6
16:20 – 16:50	**Coffee Break & Poster Viewing**	
16:50 – 17:10	J. Shimoda	The effects of escaping cosmic-rays from Supernova Remnants in the interstellar medium

Session 7: PWN Diversity; Structures, Bowshocks and Magnetar Wind Nebulae

17:10 – 17:45	<u>R. Kothes</u>	A Radio Eye on Pulsar Wind Nebulae
17:45 – 18:05	M. Arias	The Crab nebula at 150 MHz and sub-arcsecond resolution with the LOFAR long baselines
18:05 – 18:30	1slide/1min	25 Poster Presentations - Sessions 6, 7, 8 & 9
20:15	Buses depart from Minoa Palace Resort to Almira beach bar & restaurant	
20:30 – 00:00	**Conference Banquet @ Almira beach bar & restaurant**	
00:15	Buses depart from Almira beach bar & restaurant to Minoa Palace Resort	

Friday June 14

Morning Session (Chairs: P. Slane & N. Bucciantini)

Session 7: PWN Diversity; Structures, Bowshocks and Magnetar Wind Nebulae

09:00 – 09:35	<u>O. Kargaltsev</u>	Pulsar Wind Nebulae in X-rays: Population Properties, Outstanding Results, and Open Questions
09:35 – 09:55	S. Lazarevic	Discovery of bow-shock Pulsar Wind Nebulae in new generation radio continuum surveys
09:55 – 10:15	P.-S. Ou	Structure of the Pulsar Wind Nebula in SNR 0540-69.3 Revealed by ALMA
10:15 – 10:35	L. Tenhu	Spatial variations and breaks in the optical-NIR spectra of the pulsar and PWN in SNR 0540-69.3

Session 8: SNRs and PWNe as PeVatrons

10:35 – 10:55	E. Simon	Maximum energy cosmic-rays from Galactic SNe: simulations of quasi-parallel and -perpendicular shocks
10:55 – 11:00	Best PhD poster award	
11:00 – 11:30	**Coffee Break & Poster Viewing**	
11:30 – 12:05	<u>F. Acero</u>	The what, where, and who of Galactic PeVatrons as probed by high-energy observations
12:05 – 12:25	R. Yang	LHAASO observations on the SNR Cassiopeia A
12:25 – 12:45	l. Sushch	SNRs in stellar clusters: particle acceleration
12:45 – 13:05	M. Lemoine-Goumard	Hadronic particle acceleration in the SNR SN 1006 as traced by Fermi-LAT observations
13:05 – 14:30	**Lunch**	

Afternoon Session (Chair: S. Safi-Harb)

14:30 – 15:05	<u>K. Mori</u>	Multi-wavelength observations of Galactic PeVatrons

Session 9: SNR/PWN/Compact Objects Associations, Interaction and Evolution

15:05 – 15:40	S. Katsuda	High-resolution X-Ray spectroscopy of Supernova Remnants: from dispersive spectrometers to microcalorimeters
15:40 – 16:00	E. Greco	New constraints on the Pulsar Wind Nebula in SN 1987A from multiwavelength observations and MHD modeling
16:00 – 16:20	D. Torres	Pulsar Wind Nebulae phenomenology and evolution at and beyond reverberation
16:20 – 16:50	**Coffee Break & Poster Viewing**	
16:50 – 17:25	A. Borghese	The zoo of isolated neutron stars
17:25 – 17:45	T. Kravtsov	Discovery of new oxygen-rich supernova remnants
17:45 – 18:00	P. Slane	Closing Remarks

Saturday June 15

08:30 – 18:30	**Excursion#2: Full-day excursion to Anoskeli winery & olive mill and to Paleochora, the "Libyan Bride"** Buses depart/arrive from/to Minoa Palace

END OF CONFERENCE

CONFERENCE POSTERS

Session 1: Populations/Surveys and Classifications of SNRs and SNe

S1.1	F. Bocchino	GalRSG: A long-term monitoring campaign of Galactic Red Supergiants and the quest for SN explosions' premonitory signs
S1.2	F. Bocchino	Search for Gamma-ray emission from SNRs in the Large Magellanic Cloud: Preliminary results of a new cluster analysis at energies above 3GeV
S1.3	C. Burger-Scheidlin	Gamma-ray detection of newly discovered Ancora supernova remnant: G288.8–6.3
S1.4	A. Castrillo	Supernova remnant catalog in the PHANGS survey
S1.5	M. Filipovic	Mysterious Odd Radio Circle near the Large Magellanic Cloud - An Intergalactic Supernova Remnant?
S1.6	B. Gamache	Characterization of M51 supernovae remnants with the imaging spectrometer SITELLE
S1.7	D. A. Green	Statistics of Galactic Supernova Remnants
S1.8	A. Ingallinera	Studying SNRs and their environment with high-resolution radio spectral index maps
S1.9	A. Khokhriakova	SNR G321.3-3.9 observed with multi-band radio data and SRG/eROSITA
S1.10	I. Leonidaki	Disentangling the evolutionary paths of Supernova Remnants: observational evidence of (non) multi-wavelength emission
S1.11	I. Leonidaki	A systematic meta-analysis of physical parameters of Galactic SNRs
S1.12	T.-X. Luo	Investigation of Galactic supernova remnants and their environment in 26.6°<l<30.6°, |b|≤ 1.25° using radio survey
S1.13	S. Mantovanini	Low radio frequency images of the southern Galactic plane for supernova remnant detection
S1.14	M. Michailidis	X-ray counterpart detection and gamma-ray analysis of the SNR G279.0+01.1 with eROSITA and Fermi-LAT
S1.15	R. Kothes	An L-band Panoramic View of Galactic Supernova Remnants with the Australian SKA Pathfinder
S1.16	S. Panjkov	The Effects of Metallicity on the LMC Core-Collapse Progenitor Mass Distribution
S1.17	N. O. Pinciroli Vago	DeepGraviLens: a multi-modal architecture for classifying gravitational lensing data
S1.18	Z. Smeaton	Discovery of new, young Galactic SNR (G329.9-0.5)

Session 2: SNe and SNRs with Circumstellar Interactions

S2.1	M. Arias	Probing supernova remnant VRO 42.05.01's progenitor properties with IRAM 30m observations
S2.2	R. Baer-Way	A multi-wavelength autopsy of a young interacting supernova to unveil its progenitor
S2.3	M. Chatzopoulos	Radiative Transfer Modeling of Astrophysical Transients Powered by Circumstellar Interaction
S2.4	W.-Y. Chen	Multidimensional Radiation Hydrodynamics Simulations of Supernova 1987a Shock Breakout
S2.5	W.-Y. Chen	2D Rad-Hydro Shock Breakout Simulations on RSG with CSM

S2.6	A. Chrimes	Clues (and conunumdrums) from the circumstellar media around extreme extragalactic transients
S2.7	T. Court	Type Ia Supernova Remnants in Different Circumstellar Environments
S2.8	J. Horvat	An XMM-Newton study of several nonradiative filaments in the northeastern rim of the Cygnus Loop
S2.9	M. Ichihashi	The thermal relaxation process in collisionless shock of SN1006
S2.10	W. Jacobson-Galan	Final Moments: Observational Properties and Physical Modeling of “Flash Spectroscopy” Supernovae
S2.11	B. Liu	Investigation into SNR-accelerated CRs at the prospect of future MeV gamma-ray detectors
S2.12	L.-D. Liu	Light curves of Multiple Ejecta-circumstellar Medium Interactions
S2.13	E. Makarenko	How do supernova remnants cool? Morphology and optical emission lines
S2.14	M. Matsuura	Infrared emission of supernova remnants in the Small Magellanic Cloud
S2.15	A. Mercuri	Spectral Analysis of Chandra data on selected regions of the Supernova Remnant Cassiopeia A
S2.16	T. Murase	Molecular Clouds associated with middle-aged gamma-ray Supernova Remnants W41 and G22.7–0.2
S2.17	A. Nagy	How can circumstellar interaction explain the special light curve features of Type Ib/c supernovae?
S2.18	S. Orlando	Constraining the CSM structure and progenitor mass-loss history of SN 2014C through 3D hydrodynamic modeling
S2.19	B. H. Pál	A possible circumstellar interaction of SN2004gq
S2.20	O. Petruk	Density and magnetic field gradients in Tycho SNR
S2.21	G. Prete	Interaction of a Supernova Remnant with background interstellar turbulence
S2.22	L. Sun	Probe charge exchange and resonant scattering in Magellanic Cloud supernova remnants with spatially-resolved high-resolution X-ray spectroscopic study of oxygen lines
S2.23	I. Sushch	Role of reflected shocks in particle acceleration in supernova remnants
S2.24	A. Suzuki	Multi-dimensional simulations of interaction-powered supernovae
S2.25	H. Suzuki	Global and Rapid Deceleration of X-Ray Knots and Rims of RCW 103
S2.26	K. Tsuge	Shocked Molecular Clouds in the LMC SNR N132D Revealed by ALMA ACA
S2.27	S. Ustamujic	Modeling the mixed-morphology supernova remnant VRO 42.05.01

Session 3: SN/SNR Progenitors, Central Engines, Explosion Models

S3.1	E. Abdikamalov	Exploring supernova gravitational waves with machine learning
S3.2	M. Anazawa	Estimation of progenitor of Keplers SNR with precision X-ray spectroscopic analysis
S3.3	B. Arbutina	Modeling Binary Systems That Survive Supernova Explosions and Give Rise to Gravitational Waves
S3.4	B. Barna	Different, but still same: on the common(?) origin of the peculiar Type Iax SNe

S3.5	E. Batziou	The Long-time Evolution of Accretion-Induced Collapse of White Dwarfs to Neutron Stars
S3.6	Z. R. Bodola	Massive Progenitor Parade of Stripped-Envelope Supernovae
S3.7	A. Z. Bonanos	Evidence for episodic mass loss in red supergiants from the ASSESS project
S3.8	K. A. Bostroem	Considering the Single and Binary Origins of the Type IIP SN 2017eaw
S3.9	M. Bugli	Numerical models of magneto-rotational supernovae: dynamics, multi-messenger signals, and explosive nucleosynthesis
S3.10	M. Bugli	3D MHD core-collapse supernovae code comparison: the impact of numerics on central engine's simulations
S3.11	E. Christodoulou	Obtaining accurate parameters of Type IIP progenitors in NGC 6822, IC 10 & WLM
S3.12	L. Dang	Typing supernova remnant G352.7−0.1 using XMM-Newton X-ray observations
S3.13	B. Dinçel	Possible pre-supernova binary companion to the progenitor of the supernova remnant IC 443
S3.14	O. Eggenberger Andersen	Black Hole Supernovae and their Equation-of-state Dependence
S3.15	J. I. Gonzalez-Hernandez	Searching for surviving stellar companions of historical galactic type Ia supernovae
S3.16	A. Holas	Electron-capture supernovae - Thermonuclear explosion or gravitational collapse? - The fate of sAGB stars on a knife's edge
S3.17	C. M. Irwin	An unexplored regime of shock breakout: the effect of rapid thermalization on the observed spectrum
S3.18	M. Kalitsounaki	Discovery of an extreme Red Supergiant in the LMC transitioning to a Blue Supergiant
S3.19	E. Kasdagli	Improving Supernova Prescriptions in Binary Population Synthesis Using Detailed Stellar Profiles
S3.20	J. Luo	3D Simulation of SN~Ia SNR: Effects of Companion Star and Progenitor System
S3.21	K. Matsunaga	Formation of Mg-rich SNRs by shell merger and its effect on the explodability
S3.22	G. Munoz-Sanchez	[W60] B90: a mass-losing luminous RSG in the LMC interacting with the CSM
S3.23	T. Narita	Progenitor constraint with CNO abundances of circumstellar material in supernova remnants
S3.24	Z. Niu	The binary progenitor for Type IIP supernovae
S3.25	C. Omand	Probing Energetic Infant Pulsars with Supernova Emission Lines
S3.26	K.-C. Pan	Stellar Mass Black Hole Formation and Multimessenger Signals from Core-collapse Supernova Simulations
S3.27	G. Pignata	Three years observations of the nearby type II SN2008bk
S3.28	A. Rest	The Historic Light Curve of Eta Car's Great Eruption from its Light Echoes
S3.29	P. Ruiz-Lapuente	SN Ia supernova remnant with M dwarf companions
S3.30	R. Sawada	'56Ni problem' in Canonical Supernova Explosion
S3.31	M. Shahbandeh	The Life Story of Stripped-Envelope Supernovae as told through JWST Observations
S3.32	M. Solar	Binary progenitor systems for Type Ic supernovae
S3.33	T. Tanaka	Expansion Measurements of Tycho's Supernova Remnant and Their Implications of the Progenitor System

S3.34	H. Uchida	Possible evidence of a jet-induced explosion found from X-ray and radio observations of a peculiar SNR G0.61+0.01
S3.35	J. Weng	Upper Limits of ^{44}Ti Decay Emission in Four Nearby Thermonuclear Supernova Remnants

Session 4: SNR Structure, Ejecta and Evolution

S4.1	M. Agarwal	X-ray diagnostics of Cassiopeia A's "Green Monster": evidence for dense shocked circumstellar plasma
S4.2	S. Akras	Spectroscopic analysis tool for intEgraL fieLd unIt daTacubEs (SATELLITE): The case of SNR 0509-68.7
S4.3	M. Anđelić	On the origin of the North Polar Spur
S4.4	Y. Chen	A Monte-Carlo Simulation on Resonant Scattering of X-ray Line Emission in Supernova Remnants
S4.5	Y.-H. Chi	Thermal X-ray Emission in the Western Half of the LMC Superbubble 30 Dor C
S4.6	P. Das	Observational Study of the Reversed Shocked Ejecta in SNR 0509-67.5
S4.7	D. Dickinson	High Resolution Mapping of the Unshocked Ejecta in Cassiopeia A
S4.8	M. Fontaine	Theoretical and Experimental Simulations of Colliding Blast Waves
S4.9	B. Giudici	Hydrodynamic instabilities in three-dimensional simulations of neutrino-driven supernovae of 14 red supergiant progenitors
S4.10	R. Giuffrida	Measuring the initial mass of 44Ti in SN 1987A through the 44Sc emission line
S4.11	L. Godinaud	Mapping the 3D dynamics and spectral properties of Tycho's SNR in X-rays
S4.12	T. Ko	The multi-layer structure of SNR 1181 with a white dwarf in its center
S4.13	B.-C. Koo	JWST Observations of the Cassiopeia A Supernova Remnant: Near-Infrared Colors of Supernova Ejecta
S4.14	D. Leahy	On emission measures and element densities and masses inferred from XSPEC
S4.15	D. Leahy	Models for supernova remnants with reverse shock emission
S4.16	E. Makarenko	Thermal X-ray emission from supernova remnants in 3D (M)HD simulations
S4.17	S. Mandal	Measurement of anisotropies in observed Supernova Remnants and their interpretation using hydrodynamical models
S4.18	M. Ono	Molecular formation in the ejecta of SN 1987A based on three-dimensional hydrodynamical models
S4.19	S. Panjkov	Morphological Insights into the SN progenitors of the Small Magellanic Cloud
S4.20	G. Paylı	Investigation of supernova remnant IC 443 and G189.6+3.3 with LAMOST
S4.21	L. Romano	Cloud Formation by Supernova Implosion
S4.22	V. Sapienza	Probing Shocked Ejecta in SN 1987A: A novel diagnostic approach using XRISM-Resolve
S4.23	N. Sanches Sartorio	New Analytical Solutions for Supernova Shocks
S4.24	L. Sun	Evolution of X-ray Gas in SN 1987A from 2007 to 2021: Ring Fading and Ejecta Brightening Unveiled through Differential Emission Measure Analysis

S4.25	J. C. Toledo-Roy	Simulated non-thermal emission of the supernova remnant G1.9+0.3
S4.26	D. Urošević	A method for determination of evolutionary status of supernova remnants from radio data
S4.27	B. van Baal	Nebular Phase Stripped Envelope Supernovae in 3D
S4.28	K. Vargas Rojas	Study of non-thermal emission of Kepler's SNR with MHD numerical simulations.

Session 5: Shock Physics, Particle Acceleration, Polarization in SNRs and PWNe

S5.1	F. Acero	How I learned to stop trusting my X-ray spectral best fits and love nested sampling
S5.2	B. Ball	Radio Polarization Studies of Galactic Supernova Remnants with ASKAP
S5.3	D. Castro	The Expansion and Width of the Synchrotron Filaments Associated with the Forward Shocks of SNRs
S5.4	L. Del Zanna	Relativistic MHD turbulence simulations and synchrotron polarization properties of Pulsar Wind Nebulae
S5.5	R. Ferrazzoli	Discovery of a shock-compressed magnetic field in the NW rim of the young SNR RX J1713.7-3946 with X-ray polarimetry
S5.6	R. Giuffrida	Evidence for proton acceleration and escape from the Puppis A SNR using Fermi-LAT observations
S5.7	E. Greco	Jitter radiation as an alternative mechanism for the nonthermal emission in Cassiopeia A
S5.8	J. Hewitt	Resolving the gamma-ray supernova remnant IC 443 with Fermi LAT and VERITAS
S5.9	J. Hewitt	Two new radio-dim, gamma-ray-bright supernova remnants
S5.10	S. Knežević	Shock geometry and physics in the supernova remnant SNR 0509-67.5
S5.11	P. Kostić	Kinetic-based CFD modeling of synchrotron emission spectra at fast SNRs
S5.12	Y. Ohshiro	A self-consistent model of shock-heated plasma in non-equilibrium states for direct parameter constraints from X-ray observations
S5.13	V. Sapienza	Time evolution of the synchrotron X-ray emission in Kepler's SNR: the effects of turbulence and shock velocity
S5.14	X. Shi	The production of unstable cosmic-ray isotopes in supernovae clusters
S5.15	J. D. Slavin	Modeling Shock Emission Including Dust Destruction
S5.16	K. Stasiewicz	Reinterpretation of the Fermi acceleration of cosmic rays in terms of the ballistic surfing acceleration in supernova shocks
S5.17	S. J. Tanaka	A Self-regulated Stochastic Acceleration Model of Pulsar Wind Nebulae
S5.18	D. Tateishi	Suzaku/XIS study of the acceleration environment of bilateral SNR RX J0852.0-4622
S5.19	S. Ustamujic	Modeling the supernova remnant RX J1713.7 – 3946: particle acceleration, gamma-ray emission, and neutrino flux

Session 6: SN/SNR dust, environments, feedback

S6.1	N. Izumi	CI/CO abundance ratio of shock-excited gas in the Magellanic Supernova Remnant N63A

S6.2	F. Kirchschlager	Dust destruction in the clumpy remnant Cassiopeia A: impact of inhomogeneous dust distributions
S6.3	N. Sanches Sartorio	The impact of CSM properties on the dust destruction by supernovae forward shocks
S6.4	H. Sano	ALMA Observations of Supernova Remnant N49 in the Large Magellanic Cloud. II. Non-LTE Analysis of Shock-heated Molecular Clouds
S6.5	T. Scheffler	Dust destruction by supernova remnant forward shocks in a turbulent interstellar medium
S6.6	A. Singleton	Constraining the progenitor properties of the Type Ib supernova iPTF13bvn through its environment with HST and MUSE
S6.7	D. Souropanis	Time-dependent feedback of core-collapse supernovae from binary progenitors via detailed binary population synthesis models
S6.8	T. Tu	A Yebes W band Line Survey towards an Unshocked Molecular Cloud of Supernova Remnant 3C391: Evidence of Cosmic-Ray-Induced Chemistry
S6.9	R. Wesson	The slow formation of dust by core collapse supernovae
S6.10	M. Zhang	Not gone with the wind: survival of high-velocity molecular clouds in the Galactic Centre
S6.11	Q. Zhang	A molecular line survey toward clumps G and E in supernova remnant IC 443 with the Submillimeter Array
S6.12	Z. Zhang	Estimation of the Dust Mass with Infrared Emission and Extinction of the Supernova Remnants: G156.2+5.7, G109.1-1.0, G166.0+4.3, G93.7-0.2
S6.13	S. Zsíros	Disentangling possible dust components of core-collapse supernovae within a Bayesian framework

Session 7: PWN Diversity; Structures, Bowshocks and Magnetar Wind Nebulae

S7.1	J. Alford	Cosmic Ray Leptons Escaping from CTA 1?
S7.2	Y. Chen	“Mirage” and large offsets in the data as a result of asymmetric CR diffusion
S7.3	L. V. da Conceição	Using CFHT’s SITELLE to probe the long-sought shell in the Crab nebula
S7.4	S. Gagnon	Chandra X-ray Observations of PSR J1849-0001 and its Pulsar Wind Nebula
S7.5	X. Li	An Exploration of Misaligned Outflows in Pulsar Wind Nebulae
S7.6	S. Mandal	Diagnosis of Pulsar Wind Nebula dynamics using their filamentary structure
S7.7	K. Yan	Pulsar halos as an origin of the Galactic diffuse TeV-PeV emission: Insight from LHAASO and IceCube

Session 8: SNRs and PWNe as PeVatrons

S8.1	R. Brose	Fast Blue Optical Transients as cosmic-ray sources
S8.2	R. Diesing	The Maximum Energy of Shock-Accelerated Cosmic Rays
S8.3	Y. Gallant	Pulsar Wind Nebulae and their halos observed in TeV and PeV gamma rays
S8.4	S. Lazarevic	Radio-continuum view of PeVatrons
S8.5	Y. Li	Multi-Messenger Modeling of the Monogem Pulsar Halo
S8.6	B. Mac Intyre	The Manatee Nebula W50-SS433: a Galactic PeVatron?

S8.7	I. Sander	Pulsar Wind Nebulae and PeVatrons: A Case Study of PWN G309.92-2.51
S8.8	N. Tsuji	Search for molecular clouds associated with PeVatrons by the Nobeyama 45-m radio telescope: the case of LHAASO J0341+5258
S8.9	J. Woo	Revisiting Cassiopeia A after a decade: the first spatially resolved synchrotron X-ray variability above 15 keV by NuSTAR

Session 9: SNR/PWN/Compact Objects Associations, Interaction and Evolution

S9.1	J. Ahlvind	Late-time X-ray observations Core-Collapse Supernovae - constraints on emission from compact objects and CSM interaction
S9.2	A. M. Moaz	Multi-Wavelength Modelling of the Pulsar Wind Nebulae Kes 75 & HESS J1640-465
S9.3	J. Suherli	A-MUSE-ing Views of the Central Environment of the Vela Jr. and 1E0102-72.3 Supernova Remnants

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Supernova Remnants III
An Odyssey in Space After Stellar Death
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Opening Plenary

Advances in the X-Ray, Radio, Infrared, and Optical Regimes for the Detection and Study of Galactic and Extragalactic SNRs

Invited Plenary Talk

Robert Fesen

Dartmouth College, USA

Abstract

Over the next decade, new spaced-based and ground-based observatories will revolutionize our ability to detect and study both Galactic and extragalactic supernova remnants. The advent of the JWST marks the start of the revolution for near infrared SN/SNR studies, but similar advances will also be made in the radio, X-ray, and optical regimes. I will briefly discuss powerful upcoming observations, and how these new data will impact both SN explosion investigations and SNR models.

Session 1.

Populations/Surveys and Classifications of SNRs and SNe – Oral Talks

Supernova remnant population in nearby galaxies

Invited Talk

Manami Sasaki

Dr. Karl Remeis Observatory, Friedrich-Alexander-University Erlangen-Nürnberg, Germany

Abstract

Supernova remnants (SNRs) are the aftermath of stellar explosions, which inject large amounts of energy into the interstellar medium (ISM), carving out new structures and transferring kinetic energy to the ISM. They also act as recycling centres, which return elements processed in stars to the ISM, and cosmic particle accelerators. The evolution of SNRs can be best studied in radio continuum, optical line emission, and soft X-rays. While it is difficult to observe these sources in our own Galaxy due to confusion of objects and absorption by matter in the Galactic plane, the Magellanic Clouds as well as the nearby spiral galaxies are ideal targets to study both particular SNRs in detail and the SNR population in a galaxy as a whole. Various multi-wavelength studies of SNRs in the nearby galaxies have been carried out, in particular, using X-ray telescopes like XMM-Newton or Chandra, and in the past years also with the X-ray all-sky survey performed with eROSITA. We will present a summary and the latest results on the study of SNR populations in galaxies.

The future is here! Diprotodon's, Potoroo's, Kyklos, ORC's and other new SNR wonders of radio surveys

Oral Talk

Miroslav Filipovic

Western Sydney University, Australia

Abstract

This is an exciting time for the discovery of SNRs and PWNe in our and other nearby galaxies. They offer an ideal laboratory as they are near enough to be resolved yet located at relatively known distances. Various new-generation surveys through the entire waveband reflect a major opportunity to study different objects and processes in the elemental enrichment of the interstellar medium (ISM). SKA pathfinders' observations in radio regimes with high sensitivity detect new SNRs and PWN in our Galaxy and the MCs, which are either old and too faint, young and too small, or located in a too confusing environment and have thus not been detected yet. In addition, the SKA pathfinders' observations also allow high-resolution polarimetry and are key to the study of the energetics of accelerated particles as well as the magnetic field strength and configurations. Gamma-ray studies provide answers to the long-standing question in high-energy astrophysics: Where do cosmic rays come from? The gamma-ray emission seen from some middle-aged SNRs is now known to be from distant populations of cosmic rays (probably accelerated locally) interacting with gas, but there is still much work to be done in accounting for the Galactic cosmic-ray flux. Young PeV gamma-ray supernova remnants require different techniques to address the question of cosmic-ray acceleration. The Cherenkov Telescope Array will allow us to do this. I will review the most recent scientific outcomes from various new high-resolution (arcsec) and sensitivity surveys such as ASKAP, MWA, ATCA and MeerKAT (radio). This is in addition to large multi-frequency surveys from XMM-Newton & eROSITA (X-rays), Herschel and Spitzer (IR), MCELS (optical) and HESS (gamma rays).

Discovery of ∼2200 new supernova remnants in 19 nearby star-forming galaxies using MUSE spectroscopy

Oral Talk

Li Jing[1], Kathryn Kreckel[1], Sumit Sarbadhicary[2], Knox Long[3], Oleg Egorov[1], Brent Groves[4] et al.

[1]Heidelberg University - Astronomisches Rechen-Institute, Germany, [2]Ohio State University, USA, [3]STScI, USA, [4]The University of Western, Australia

Abstract

Supernova feedback, injecting energy and turbulence into the interstellar medium (ISM), profoundly influences star formation processes and is crucial for comprehending galaxy formation and evolution. Establishing a statistical count of Supernova Remnants (SNRs) enables us to quantify supernova feedback. SNRs exhibit distinctive emission line ratios and kinematic signatures, evident in optical spectroscopy. Leveraging Integral Field Unit (IFU) data from the PHANGS-MUSE project, we identified 1,166 SNRs and 1,067 SNR candidates in 19 nearby galaxies at ~ 100 pc scales, employing five different optical diagnostics. To account for photoionization-associated line emissions (HII regions and diffuse ionized gas), we utilized [S II]/Hα and [O I]/Hα line ratio maps along with Hα surface brightness. Velocity dispersion maps and line ratio diagnostic diagrams also facilitated object selection. Our SNR sample is robust; in the well-studied M83, all identified SNRs exist in literature catalogs, along with 77% of our SNR candidates. Across all galaxies, the SNRs in our 19 galaxies exhibit distinct properties from HII regions in [N II]/Hα, [S II]/Hα, and velocity dispersion. Of the five criteria, [O I]/Hα proved most effective, selecting 1,368 (62%) objects in our parent sample. Expanding our analysis to 20 Mpc distances, we successfully recovered SNRs blended with H II regions, achieving sample sizes within a factor of 2 of the expected values for these galaxies. With the increasing use of IFU observations in extragalactic galaxies, our automated approaches hold great potential for significantly expanding SNR samples in the future.

New larger sample of Supernova Remnants in NGC 7793 using MUSE IFS

Oral Talk

Maria Kopsacheili [1], C. Jiménez-Palau[1], L. Galbany[1], P. Boumis[2] and R. González-Díaz[3]

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Abstract

Study of Supernova Remnant (SNR) demographics and their physical properties is very important in order to understand their role in galaxies. Many photometric and spectroscopic studies of SNRs, have been carried out in our Galaxy but also in extragalactic environments. The most common means for the SNR identification in the optical regime, is the use of the flux ratio of the [S II] ($\lambda\lambda$6717, 6731) to Hα (λ6563) emission lines. However, this diagnostic is biased against low excitation SNRs. For this reason, we have developed new diagnostics that combine 2 and 3 emission line ratios along with a Support Vector Machine model, that efficiently differentiate SNRs from HII regions. These diagnostics recover up to 35% of the SNRs that we miss using the traditional diagnostic tool, which is very important in order to obtain more complete samples of SNRs (i.e. SNRs of different physical properties) and consequently to more efficiently explore the feedback processes to the host galaxy. We apply these diagnostics on Integral Field Unit (IFU) data of the galaxy NGC 7793. New SNR populations are presented, along with the distributions of their physical properties and their luminosity functions. Chandra data of this galaxy have been also studied, revealing at least 4 new candidate X-ray SNRs.

Environmental effects on the LMC SNR population

Invited Talk

You-Hua Chu

Institute of Astronomy and Astrophysics, Academia Sinica, Taiwan

Abstract

The Large Magellanic Cloud (LMC), at a distance of 50 kpc, is so nearby that its SNRs can be studied with high resolution at multi-wavelengths and their underlying stellar population can be resolved to assess their masses and evolutionary stages. More than 60 SNRs have been confirmed in the LMC. While the majority are core-collapse SNRs, about 15 have been identified as Type Ia SNRs based on SN ejecta abundances derived from X-ray spectra, and the 5 youngest Type Ia SNRs further exhibit Balmer-dominated shells. This large sample of C-C and Type Ia SNRs in the LMC provide a unique opportunity for us to investigate empirically the interstellar environmental effects on the physical properties of SNRs, and use the underlying stellar populations to constrain the possible nature of the SN progenitors. M33 is too far away for X-ray observations to allow spectral identification of Type Ia SNRs; however, the absence of young Balmer-dominated Type Ia SNRs in M33. The sharp contrast between the LMC and M33 in the young Type Ia SNR population is not easy to explain.

eROSITA study of the LMC SNRs

Oral Talk

Federico Zangrandi, Manami Sasaki

Dr. Remeis Observatory (FAU), Germany

Abstract

Supernova remnants (SNRs) emit at different wavelengths over the entire electromagnetic spectrum. A complete galactic sample of SNRs is important for understanding the evolution of different stellar populations as well as the chemical enrichment and the energy budget inside a galaxy. The best laboratory for the study of SNR population in a galaxy is the Large Magellanic Cloud (LMC) as it is the nearest star-forming galaxy with low absorption along the line of sight. The eROSITA telescopes are the best instruments available to conduct such a survey in X-rays due to its large field of view and high sensitivity in the soft X-ray band. We present the results on the SNR population in the LMC obtained from the eROSITA all-sky survey. The complete coverage of the LMC and its surroundings provided by eROSITA enabled us to investigate the very recent SNR candidate detected in the radio band using ASKAP interferometry, along with other SNR candidates proposed in radio and optical. Furthermore we present the detection of new SNR candidates never detected by any other X-ray telescope before. Of particular interest is the increasing population of SNRs detected outside of the main body of the galaxy which have been recently followed up by deep observations with XMM-Newton.

The many faces of type Ia SNRs: What can X-Ray observations tell us about their progenitors and explosion mechanism?

Oral Talk

Cole Treyturik, Samar Safi-Harb and Gilles Ferrand

University of Manitoba, Canada

Abstract

Supernova explosions come in two broad types, but these classifications are seldom sufficient to accurately describe the differences between – and the mechanisms responsible for – the different types of explosions, with even Type Ia supernovae exhibiting a wide range of possible formation channels which result in explosions that can be markedly different. These differences in explosion properties can result in differences in the resulting supernova remnant, in both their morphologies and their compositions, but the relation between these two has not been fully explored. We present our current progress on a comprehensive, systematic X-ray survey of 17 confirmed or suspected Ia SNRs, using over 6.5Ms of archival *XMM-Newton* and *Chandra* data to perform both spatially-resolved spectroscopic studies as well as morphological studies for each object, with a goal to better classify and connect the remnants to their supernova progenitors. We also make the case for improved nucleosynthesis models for Type Ia supernovae, emphasising the need for models that address the wider variety of formation channels.

The MeerKAT view on Galactic supernova remnants

Oral Talk

Sara Loru

INAF - Osservatorio Astrofisico di Catania, Italy

Abstract

The bulk of the SNR emission lies in the radio band, which represents a crucial window for the study of these objects. A comprehensive understanding of the different radiation mechanisms that take place in SNRs can be achieved through the combined study of: the global spectral index; the curvature of the integrated spectrum; the local variations of the spectral index within the remnant. In this context, a great step forward is going to be done thanks to the Square Kilometre Array (SKA) pathfinders and precursors, which provide images with unprecedented sensitivity and resolution for a very huge sample of objects. In this talk, I will present the results of both integrated and spatially-resolved spectral characterization of 28 Galactic SNRs, using the SARAO MeerKAT legacy Galactic Plane Survey (SMGPS) data at 1.284 GHz and the GaLactic and Extragalactic All-sky Murchison Widefield Array (GLEAM) data (0.074−0.200 GHz). The high resolution SMGPS images allowed us to correctly recover the morphology of these SNRs, distinguishing them from unrelated sources or identifying new emission regions associated with them and never observed before. By exploiting the large frequency span between the SMGPS and MWA data, we firmly constrained the integrated spectral indices, often highlighting a different spectral behavior with respect to the previous studies. We produced sensitive 0.154−1.284 GHz spectral index maps through which we revealed spectral variations related to phenomenologically different remnant regions, providing a powerful tool to constrain the cosmic ray acceleration mechanisms resulting in SNRs from peculiar shock conditions and/or ISM interaction. Finally, we used the integrated spectral indices obtained in this work to investigate the spectral index distribution of our 28 SNRs and we discussed it in comparison with that obtained by considering the spectral indices available in the literature.

Light echoes of an unknown supernova remnant in 30 Doradus

Oral Talk

Armin Rest[1], C. Woods[2], J. Mack[1], E. Johnson[3], E. Sabbi[4], J. Jencson[5], X. Li[3], R. Angulo[3]

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Abstract

We report the discovery of scattered light echoes in 30 Doradus, otherwise known as the Tarantula Nebula, likely resulting from a supernova explosion. Two light echo arclets are visible in a difference image created from Hubble Space Telescope WFC3 images from 2011 and 2014 in the F775W band. We show that the source of these light echoes is likely a SN not older than 3000 years and within 0.75 deg of the light echoes. It is therefore unlikely that these light echoes are associated with any of the known supernova remnants, and future observations might reveal a yet undiscovered young supernova in a low density region.

Session 1.

Populations/Surveys and Classifications of SNRs and SNe – Posters

GalRSG: A long-term monitoring campaign of Galactic Red Supergiants and the quest for SN explosions' premonitory signs

Poster

Fabrizio Bocchino[1], S. Orlando[1], M. Miceli[2], O. Petruk[1,3], A. Pastrorello[1], M. Limongi[1,4,5], and A. Chieffi[1,5,6]

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Abstract

The studies of pre-supernova outbursts have received lot of attention because of their high diagnostic power for the nature of the supernova progenitor and the implications on the structure of the circumstellar medium (CSM) in the immediate surrounding of the exploding SNe. So far, the study of the outbursts have been mostly confined to archive data of extragalactic SNe, resulting in a handful of cases in which SN precursors have been securely identified. These 'a-posteriori' surveys have been proved very useful to characterize the diversity of the SNe 'zoo', but they suffer a bias against the very rich $L \leq 10^5 L_\odot$ population of low-mass Red Supergiants (RSG) and they lack homogeneous pre-SN data. To overcome this limitation, we assembled a literature-based catalog of a coeval and co-distant sample of galactic RSGs in the Scutum-Crux region, which gives us the possibility to change the observational paradigm of pre-SN outburst studies. We launched a long-term monitoring campaign aimed to characterize the multi-color light curves of this large sample of RSGs, to detect late-stage outbursts and to compare them with very recent models of the final phases of low-mass RSGs before SN explosion, thus possibly predicting core collapse of specific objects before it occurs. We present this on-going project and some preliminary results.

Search for γ-ray emission from SNRs in the Large Magellanic Cloud: Preliminary results of a new cluster analysis at energies above 3 GeV

Poster

A. Tramacere[1], E. Massaro[2], R. Campana[3], F. Bocchino[4], S. Orlando[4], and M. Miceli[5]

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Abstract

In the previous paper (Campana et al. 2022, MNRAS 515, 1676) we presented the results of a search for γ-ray emission from SNRs in the Large Magellanic Cloud (LMC) based on the detection of concentrations in the arrival direction Fermi-LAT images of photons at energies higher than 10 GeV. In that study we considered data obtained in the time window from August 4 2008 to August 4 2020 (12 years) and applied two different methods of clustering analysis: Minimum Spanning Tree (MST; Campana et al. 2008, 2013), and Density Based Spatial Clustering of Applications with Noise (DBSCAN; Tramacere & Vecchio 2013, Tramacere et al. 2016). In the present contribution, we report the preliminary results of a new search extended using a 15 year long (up to August 4 2023) data set and to a broad energy range (higher than 4 GeV). We confirm the results of the previous paper and found a positive indication for at least 8 new clusters with a spatial correspondence with other SNRs, increasing thus the number of remnants in LMC candidates or detected in the high energy g rays to more than 14 sources.

Gamma-ray detection of newly discovered Ancora supernova remnant: G288.8–6.3

Poster

Christopher Burger-Scheidlin[1], Robert Brose[1], Miroslav D. Filipovic[2], Pranjupriya Goswami[3], Enrique Mestre Guillen[4], Emma de Oña Wilhelmi[5], Iurii Sushch[6]

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[6]GSSI, Italy

Abstract

The supernova remnant (SNR) G288.8–6.3 was recently discovered as a faint radio shell at high Galactic latitude using observations with the Australian Square Kilometre Array Pathfinder (ASKAP) in the Evolutionary Map of the Universe (EMU) survey. We performed the first detailed investigation of the γ-ray emission from the G288.8-6.3 region, aiming to characterise the high-energy emission in the GeV regime from the newly discovered SNR, dubbed Ancora. Fifteen years of Fermi–Large Area Telescope (LAT) data were analysed at energies between 400 MeV and 1 TeV, and the excess seen in the region was modelled using different spatial and spectral models. We detect spatially extended γ-ray emission coinciding with the radio SNR, with detection significance up to 8.8σ. A radial disk spatial model in combination with a power-law spectral model with an energy flux of $(4.80\pm0.91)\times10^{-6}$ MeV cm^{-2} s^{-1}, with the spectrum extending up to around 5 GeV was found to be the preferred model. Morphologically, hotspots seen above 1 GeV are well correlated with the bright western part of the radio shell. The emission is more likely to be of leptonic origin, given the estimated gas density in the region and the estimated distance and age of the SNR, but a hadronic scenario cannot be ruled out. Ancora is the seventh confirmed SNR detected at high Galactic latitude with Fermi–LAT. The study of this new population of remnants can provide insights into the evolutionary aspects of SNRs and their properties, and further advance efforts of constraining the physics of particle diffusion and escape from SNRs into the Galaxy.

Supernova remnant catalog in the PHANGS survey

Poster

Asier Castrillo

Autonomous University of Madrid, Spain

Abstract

We will be presenting the primary results of the supernova remnants (SNR) catalog obtained from the PHANGS-MUSE survey. This survey consists of 19 nearby face-on spiral galaxies observed with the MUSE integral-field instrument at the VLT. We have developed an unsupervised machine learning clustering method that it is able to separate the different component of the ionized interstellar medium (ISM). Using this method, we found 2210 HII regions and 483 SNR. We used the emission lines within the MUSE spectral range to explore different diagnostic diagrams, searching for new demarcation lines to discriminate HII regions from SNR. We also include some theoretical models for radiative shocks (MAPPINGS) and star formation photoionized nebulae (CLOUDY). We analyze the size distribution of the SNR in relation to the local density of the ISM. And taking into account the kinematic information, we can confirm that these are radiative pressure driven SNR. Finally, using the stellar population synthesis technique we are able to derive the star formation history of the sample galaxies with a 400 pc resolution. Being able to set some constraints on the delay time distribution model for the SNR sample.

Mysterious Odd Radio Circle near the Large Magellanic Cloud – An Intergalactic Supernova Remnant?

Poster

Miroslav Filipovic

Western Sydney University, Australia

Abstract

I will report the discovery of J0624-6948, a low-surface brightness radio ring, lying between the Galactic Plane and the Large Magellanic Cloud (LMC). It was first detected at 888 MHz with the Australian Square Kilometre Array Pathfinder (ASKAP) and with a diameter of ∼196 arcsec. This source has phenomenological similarities to odd radio circles (ORCs). Significant differences to the known ORCs – a flatter radio spectral index, the lack of a prominent central galaxy as a possible host, and a larger apparent size – suggest that J0624–6948 may be a different type of object. We argue that the most plausible explanation for J0624–6948 is an intergalactic supernova remnant due to a star that resided in the LMC outskirts that had undergone a single-degenerate type Ia supernova, and we are seeing its remnant expand into a rarefied, intergalactic environment.

Characterization of M51 supernovae remnants with the imaging spectrometer SITELLE

Poster

Billy Gamache, Laurent Drissen and Carmelle Robert

Université Laval, Canada

Abstract

We present a detailed 3D study of supernova remnants in the nearby spiral M51 using data from the SIGNALS survey obtained with the imaging Fourier transform spectrometer SITELLE at the Canada-France-Hawaii telescope. Data cubes covering the entire galaxy with a sampling of 0.32”/pixel were gathered in three spectral ranges: SN3 (R = 5000 for Hα, [NII]$\lambda\lambda$6548,84 and [SII]$\lambda\lambda$6717,31), SN2 (R = 1000 for Hβ and [OIII]$\lambda\lambda$4959, 5007) and SN1 (R = 1000 for [OII]λ3727). The relatively high spectral resolution of the SN3 cube allows a precise, spatially resolved measurement of the velocity dispersion of each object. While most of the SNRs were known from previous surveys based on imagery and long-slit spectroscopy, we now provide 2D line flux and kinematical maps for all of them and found 18 new candidates. Line ratios other than the traditional [SII]/Hα are presented and discussed. Most of the SNRs show velocity dispersions (σ) in the range 30-80 km s^{-1}, which is typical for middle-aged SNRs; in some cases, the approaching and receding caps are resolved. The mean value of the [NII]/Hα of 2.15±0.12. This is significantly higher than usual ratios found in other spiral galaxies, but is expected given the high metallicity of M51. Finally, we compare the properties of SNRs with those of thousands of HII regions included in the same data cubes.

Statistics of Galactic Supernova Remnants

Poster

David A. Green

Cavendish Laboratory, University of Cambrdige, UK

Abstract

For several decades I have produced catalogues of Galactic supernova remnants (SNRs), and I will review some of the current statistical properties of SNRs, and how these have evolved. Statistical studies are better because not only has the number of identified remnants increased (with the number approximately doubling from about 150 in the 1980s to about 300 now), but also many more remnants have distance measurements available. The latter means that statistical studies no longer need to rely on the 'Σ-D' relation, which has various problems. However, the problems due selection effects still limits many statistical studies.

Studying SNRs and their environment with high-resolution radio spectral index maps

Poster

Adriano Ingallinera

INAF – Osservatorio di Catania, Italy

Abstract

Supernova remnants evolve in rich and complex environments, and their interaction is thought to have a significant impact on the Galaxy evolution. The SARAO MeerKAT Galactic Plane survey (Goeadhart et al., submitted) is supplying top-level radio images with unprecedented sensitivity at a resolution of a few arcseconds. A preliminary analysis of these data is shedding light on the environment of many known and new supernova remnants (Loru et al. in prep., Anderson et al. in prep.). As a quite common feature, many supernova remnants appear surrounded by discrete H II regions, as well as more diffuse ionized medium. In these cases, it seems possible that star formation has been triggered by the supernova progenitor or by the remnant itself. In this poster we present a more advanced analysis of the MeerKAT data, with a reprocessing aimed at creating arcsec spectral index maps and polarization maps, with the general goal to unveil signature of the interaction between the remnant and its environment. Given the huge amount of data and the computational demand of this task, this work is used as a data processing test in view of the creation of the SKA regional centers and their prototypes.

SNR G321.3-3.9 observed with multi-band radio data and SRG/eROSITA

Poster

Alena Khokhriakova[1], **S. Mantovanini**[2], **W. Becker**[3], **N. Hurley-Walker**[2], **G. E. Anderson**[2], **L. Nicastro**[4]

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Abstract

Detecting a supernova remnant (SNR) along the Galactic plane can be challenging. Any new detection reduces the discrepancy between the expected and known number of remnants. We present results from a large selection of radio and X-ray data that cover the position of G321.3-3.9. We identified G321.3-3.9 as a new SNR using data collected by several radio surveys, spanning a frequency range from 200 to 2300 MHz. Stacked eROSITA data from four consecutive all-sky surveys (eRASS:4) provide spectro-imaging information in the energy band 0.2-8.0 keV. G321.3-3.9 has an elliptical shape with major and minor axes of about $1.7^\circ \times 1.1^\circ$. From CHIPASS and S-PASS data, we calculate a spectral index $\alpha = -0.8 \pm 0.2$, consistent with synchrotron emission from an expanding shell in the Sedov Taylor phase. The eROSITA data show an X-ray diffuse structure filling almost the entire radio shell. Based on our spectral analysis, we found the temperature to be approximately 0.6 keV and the column absorption density about 10^{21} cm^{-2}. Comparing this absorption density to optical extinction maps, we estimate the distance to fall within the range of (1.0 – 1.7) kpc, considering the 1σ uncertainty range.

Disentangling the evolutionary paths of Supernova Remnants: observational evidence of (non) multi-wavelength emission

Poster

Ioanna Leonidaki[1], A. Zezas[1], K. Anastasopoulou[2], M. Kopsacheili[3], and P. Boumis[4]

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Abstract

Driven from the theoretical models that predict different wavelength emission at different evolutionary stages throughout the life of a Supernova Remnant (SNR), we have embarked the last few years on the multi-wavelength study of the SNRs within our Galaxy. Taking advantage of their proximity and their adequate number (∼300 are known to exist), the population of Galactic SNRs is the ideal sample to work on. The main objective of this campaign has been the coverage of the entire sample in narrow-band filters of SNRs' interest (i.e. Hα, [S II], [O III], Hβ) since despite the wealth of data, only ∼35% of Galactic SNRs had been observed in the optical band so far. Our goal is to build a multi-wavelength atlas of imaging and spectroscopic data of all Galactic SNRs. This talk presents the intriguing results from the first of a series undertaking the optical study of the X-ray emitting, Galactic SNRs. We quantitatively investigate their multi-wavelength radiation (optical/X-rays), compare it with their evolutionary trends, and evaluate to what extend theory matches with observations. We examine their multi-wavelength properties (e.g. L_X - $L_{H\alpha}$, L_X - L_{SII}, L_X- – [S II]/Hα), their kinematics and morphology as a function of their age and environment (e.g. distribution of shock velocities within a remnant, comparison of shock velocities with age or non-thermal emission, interaction with molecular clouds). We look into different emission mechanisms for different types of SNRs (Balmer dominated, Type II, Type Ia) while we investigate/discuss to what extend we can discriminate their progenitors (core collapse, Type Ia). Long-standing questions regarding the connection between their emission and evolution can/are dared to be answered. For example, do we expect all SNRs to have a multi-wavelength emission? Are the X-rays the dominant emission component in young SNRs while the mature ones mainly emit in the optical? If (not) so, how much the environment affect their radiation and speed up/postpone their evolutionary phases?

A systematic meta-analysis of physical parameters of Galactic SNRs

Poster

Issa Hussein-Basia[1], A. Zezas[2], I. Leonidaki[2], and M. Kopsacheili[3]

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Abstract

We present a systematic statistical study of the physical parameters (shock velocity, electron density) of the optically-emitting SNR population in our Galaxy. Due to their proximity, Galactic SNRs have the advantage of spatially resolved observations, which along with information on their age, kinematics, and dynamics, allow for testing models of SNR evolution. Based on the catalog of Green (2019), containing 294 objects we aggregated all available published information from optical studies of SNRs. Our final sample consists of 63 objects with published information. For several objects, information on multiple regions was also available allowing us to investigate spatial variations in their physical parameters. Due to the large volume of the data and the wide variations in the quality of the available information (upper/lower limits, uncertainties reported as ranges, etc.), we developed a special data homogenization approach. Our main objective is to explore the aforementioned physical properties of Galactic SNRs as a function of the SNR age and compare them with SNR evolution models. We derived the distributions of the physical parameters within individual objects, as well as for populations of SNRs grouped according to their age or ambient medium density. We find that:

(a) older objects exhibit less scatter in their physical parameters

(b) the shock velocity does not show any correlation with density

(c) there is a clear anti-correlation between shock velocity and age which is in very good agreement with theoretical models of SNR evolution

This work presents for the first time a comprehensive picture of the physical parameters of the optically emitting Galactic SNRs as a population that allows tests of SNR evolution models and provides information that can be used in feedback models.

Investigation of Galactic supernova remnants and their environment in 26.6° <l<30.6°, |b| ≤ 1.25° using radio survey

Poster

Tian-Xian Luo[1], Ping Zhou[1], Hao-Ning He[2]

[1]Nanjing University, China
[2]Purple Mountain Observatory, China

Abstract

The problem of missing Galactic supernova remnants (SNRs) refers to the issue that the currently known Galactic SNRs are significantly incomplete compared to the theoretical prediction. To expand the sample of Galactic SNRs, we use GLEAM and THOR+VGPS data across four wavebands ranging from 118 to 1420 MHz to drive a spectral index map covering the region within 26.6° <l<30.6°, |b| ≤ 1.25°, where numerous SNR candidates were recently found. By using the spectral index map of the sky region and detailed analysis of the spectral indices of individual sources, we confirmed four SNR candidates, namely G26.75+0.73, G27.06+0.04, G28.36+0.21, and G28.78-0.44, as SNRs. Additionally, we discovered an expanding molecular superbubble located in this region, discussed pulsars associated with SNR candidates, and discovered a long Hα filament that spatially overlaps with the candidate G29.38+0.10. We suggest that the problem of missing Galactic SNRs not only arises from observation limitations, but also could be due to the low-density environments of some SNRs, and the different SN explosion properties.

Low radio frequency images of the southern Galactic plane for supernova remnant detection

Poster

Silvia Mantovanini, Natasha Hurley-Walker and Gemma Anderson

Curtin University, Australia

Abstract

There is an observed discrepancy of nearly 700 sources between theory and observation for the population of supernova remnants (SNRs) in the Galactic plane. Although their mean radio spectral index of -0.5 makes these objects brighter at low frequencies, we do not have the instrumental capabilities to detect the older (and consequently larger) and fainter samples of sources. We combined data collected by two different surveys of the Murchison Widefield Array to obtain a deeper image of the plane. The wide field of view and the observing band (72-231 MHz) make this interferometer a useful resource in detecting radio emission from SNRs, that are brighter in this frequency range. The image obtained represents a unique example of combination between high resolution and sensitivity to all spatial scales (45"-15°), achieved by the union of a short-baseline survey which resolve large scale structures, with a long-baseline survey which capture the fine details of smaller scales highly decreasing the noise level. The image covers a region of the Galactic plane within 240° < l <50°, |b| ≤10° with an RMS noise varying from 10 to 2 mJy/beam across the observing band. Thanks to the wide band we will discriminate the contribution of thermal and synchrotron emissions and investigate the effects of free-free absorption either due to the presence of unshocked ejecta inside the shell or interactions with the surrounding environment outside the remnant. We could, for example, derive the Galactic cosmic-ray electron emissivity by measuring the free-free absorption of the Galactic synchrotron emission by intervening HII regions along the line of sight.

X-ray counterpart detection and gamma-ray analysis of the SNR G279.0+01.1 with eROSITA and Fermi-LAT

Poster

Miltiadis Michailidis, Gerd Puehlhofer, Andrea Santangelo, Werner Becker and Manami Sasaki

IAAT- University of Tuebingen, Germany

Abstract

Analyzing the diffuse X-ray excess near the Carina spiral arm by utilizing the first four eROSITA all-sky surveys, we report the detection of an X-ray counterpart of G279.0+01.1, a 3° supernova remnant. A partially occluded appearance of the X-ray emission in the 0.3–1.1 keV energy band is observed, likely linked to dust clouds in the nearby regions. The remnant's radio angular size, as determined by PMN data, seems to extend even further compared to the latest estimate of $\sim 2.3^\circ$ matching its X-ray counterpart size. Fermi-LAT data covering 14.5 years confirms the presence of a GeV source spatially aligned with the remnant. Results of the GeV spectral analysis and updated skymaps are provided, favoring an association of the GeV source with the remnant. The SNR is usually assumed to be at a distance of 2.7 kpc, resulting in a physical size of 140 pc. An alternative scenario that places the remnant at a much closer distance of 0.4 kpc than what was previously reported in the literature and its implications on the remnant's properties is examined.

An L-band panoramic view of Galactic supernova remnants with the Australian SKA Pathfinder

Poster

Roland Kothes [1],Brianna Ball[2]

[1]National Research Council, Canada
[2] University of Alberta, Canada

Abstract

With the Evolutionary Map of the Universe (EMU) and the Polarization Sky Survey of the Universe Magnetism (POSSUM), the touchstone radio continuum and polarization surveys of the southern hemisphere are now under way. EMU and POSSUM use the Australian SKA Pathfinder (ASKAP) telescope to image the southern sky to a sensitivity of 20 $\mu Jy/beam$ rms with a resolution of 15" over the next five years. Covering the southern hemisphere, EMU is ideal for observing the Milky Way, cataloguing stars, planetary nebulae, supernova remnants (SNRs), HII regions, and more, in various stages of evolution, while POSSUM provides sensitive polarization and Faraday rotation images to study magnetic fields in supernova remnants and pulsar wind nebulae and probing the Galactic magneto-ionic medium in their environment. The superior resolution and sensitivity of these surveys have opened up a new window of opportunity for research into Galactic SNRs. In my presentation I will discuss the analysis of a EMU/POSSUM Galactic pilot field in which we found 21 new SNR candidates over a Galactic longitude range of only 7 degrees. Only 7 SNRs where previously known in this area. With the ASKAP surveys continuing, we are applying our new techniques to all Galactic fields uncovering more of the missing supernova remnants, allowing for a better and more complete characterization of the Galactic SNR population.

The Effects of Metallicity on the LMC Core-Collapse Progenitor Mass Distribution

Poster

Sonja Panjkov, Katie Auchettl, Laura Lopez, and Enrico Ramirez-Ruiz

The University of Melbourne, Australia

Abstract

Supernovae (SNe) play an important role on the cosmological stage, however, key questions persist regarding their nature. More specifically, the precise relationship between progenitor mass and the outcome of stellar death remains uncertain. Luckily, Supernova Remnants (SNRs) present a valuable opportunity to study the endpoint of stellar evolution, as they contain imprints of the original event. Making use of the star formation history maps of Harris and Zaritsky (2009), we constrain the progenitor masses of the Large Magellanic Cloud core-collapse SNRs. Our results suggest that high mass progenitors can produce observable SNe, in line with model predictions

DeepGraviLens: a multi-modal architecture for classifying gravitational lensing data

Poster

Nicoló Oreste Pinciroli Vago[1] and Piero Fraternali

[1]INAF, PoliMi, Italy

Abstract

Gravitational lensing is the relativistic effect generated by massive bodies, which bend the space-time surrounding them. It is a deeply investigated topic in astrophysics and allows for validating theoretical relativistic results and studying faint astrophysical objects that would not be visible otherwise. In recent years, machine learning methods have been applied to support the analysis of the gravitational lensing phenomena by detecting lensing effects in datasets consisting of images associated with brightness variation time series. However, the state-of-the-art approaches either consider only images and neglect time-series data or achieve relatively low accuracy on the most difficult datasets. This work introduces DeepGraviLens, a novel multi-modal network that classifies spatio-temporal data belonging to one non-lensed system type and three lensed system types. It surpasses the current state-of-the-art accuracy results by ca. 3% to ca. 11%, depending on the considered data set. Such an improvement will enable the acceleration of the analysis of lensed objects in upcoming astrophysical surveys, which will exploit the petabytes of data collected, e.g., from the Vera C. Rubin Observatory. An extension of DeepGraviLens is also presented for counting non-lensed objects close to gravitational lenses.

Discovery of new, young Galactic SNR (G329.9-0.5)

Poster

Zachary Smeaton and Miroslav Filipovic

Western Sydney University, Australia

Abstract

It is generally accepted that the current population of known Galactic Supernova Remnants (SNRs) is only a small sample of the true population, and that this scarcity in current catalogues presents challenges in the study of these objects. The sample of young, Galactic SNRs is even sparser, and we have only discovered a fraction of the expected number. The study of Galactic SNRs is crucial to uncovering the complex physics behind these stellar explosions, and detailed studies of young SNRs are required to map their evolutionary progression and help discover their impact on the evolution of our Galaxy. In this talk, we will present the discovery of a new, young, Galactic SNR (G329.9-0.5), which we have designated as Perun, to supplement our curent sample of known, Galactic SNRs. Since there exists no recorded historical sightings of the initial supernova event, the exact age of Perun is not known. Observational evidence, however, indicates an extraordinarily young age for this SNR, giving it the potential to be the youngest Galactic SNR discovered to date. Detailed studies of a Galactic SNR at such an early evolutionary phase will provide valuable insight into the early evolution of such objects and aid in uncovering the complex physics underlying these stellar explosions. We will present an overview of the current data acquired for Perun, mainly consisting of multi-frequency observations from various telescopes including ASKAP, ATCA, MeerKAT, and Spitzer. We will then present the analysis of these observations and discuss how they are used to deduce Perun's physical properties as well as its interaction with the surrounding environment. In particular, we will focus on the evidence that is used as a justification for Perun's extremely young age estimate.

Session 2.

SNe and SNRs with Circumstellar Interactions – Oral Talks

Unveiling the progenitors of young supernovae via their circumstellar interaction

Invited Talk

Poonam Chandra

National Radio Astronomy Observatory, NRAO, USA

Abstract

One of the biggest issues in stellar evolution is understanding the different evolutionary paths of massive stars leading to a variety of explosions, such as supernovae, GRBs, etc, which remains an unsolved problem despite decades of study. This is because massive stars, unlike their low-mass counterparts, have no mapping between their initial to final mass due to extreme mass-loss processes, significantly altering the original nature of the progenitor. At the same time, mass loss plays a critical role in the final explosive outcome. Strong dependence of mass loss on binarity, magnetism, rotation, and metallicity, combined with a lack of understanding towards the dying moments of progenitors worsens the issue. Circumstellar interaction of the explosion ejecta with the surrounding winds, created via the mass loss from the massive progenitors, remains the best probe to unravel the mass loss history of the progenitors unraveling the complex nature of their progenitors. In this talk, I will review the state-of-the-art multi-wavelength study of the circumstellar interaction of various supernovae. These studies not only allow us to glimpse into this critical parameter at a time stamp but also probe the evolution of mass loss across different time scales and carry footprints of various advanced nuclear burning processes, the role of binarity, magnetism, etc.

A JWST view of the failed supernova candidate N6946-BH1

Oral Talk

Emma Beasor

University of Arizona, Steward Observatory, USA

Abstract

N6946-BH1 may represent the first case of a red supergiant (RSG) collapsing directly to form a black hole (BH), with no associated supernova (SN). If proven, this would solve the problem of missing high mass progenitors to Type IIP SNe, as well as providing a natural pathway for the formation of stellar mass BHs, as observed by LIGO/VIRGO. However, currently, we are unable to rule out that the star is still there but has enshrouded itself following a mass-loss event, similar to Eta Car's 'Great Eruption'. If this is the case, we would expect to see a brightly emitting dust shell at wavelengths $> 5\mu$m. If it has truly collapsed to a BH, there should be no luminous source left in the IR. In my talk, I will present new JWST NIRCam and MIRI photometry of BH1 which will unveil the ultimate fate of the failed supernova candidate. Whether BH1 represents the missing link to high-mass loss phases in RSGs or the first confirmed direct collapse of a massive star into a black hole, I will discuss the implications this result will have for our understanding of stellar evolution.

Latest Evolution of the X-Ray Remnant of SN 1987A: Beyond the Inner Ring

Oral Talk

Aravind Pazhayath Ravi[1], Sangwook Park[2], Svetozar A. Zhekov[3], Salvatore Orlando[4], Marco Miceli[4,5], Kari A. Frank[6], Patrick S. Broos[7], and David N. Burrows[7]

[1]University of California, Davis, USA
[2]University of Texas at Arlington, USA
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[4]INAF-Osservatorio Astronomico di Palermo, Italy
[5]Universita degli Studi di Palermo, Italy
[6]CIERA, Northwestern University, USA
[7]Pennsylvania State University, USA

Abstract

We present the latest evolution of the X-ray remnant of SN 1987A based on our Chandra imaging-spectroscopic monitoring program. Recent evolution in post-shock electron temperatures and volume emission measures suggest that the blast wave in SN 1987A is moving out of the dense inner ring structure around it, also called the equatorial ring (ER). The soft ($0.5-2.0$ keV) X-ray light curve shows a linearly declining trend (by $\sim$4.5% per year) between 2016 and 2020, as the blast wave heats the previously unknown circumstellar medium (CSM) outside the ER. While the peak X-ray emission in the latest broadband ($0.3-8.0$ keV) image is still within the ER, the radial expansion rate in the hard-band ($3.0-8.0$ keV) suggests an increasing contribution of the X-ray emission from lower-density CSM since 2012, at least partly from beyond the dense ER. It is remarkable that since 2020, the declining soft X-ray flux has stabilized around $\sim 7\times10^{-12}$ erg s^{-1} cm^{-2}, which may signal an increasing contribution from the reverse-shocked outer layers of ejecta as predicted by the 3-D magneto-hydrodynamic (MHD) models. We also report a significant Fe K line at $\sim$6.7 keV in our ACIS spectrum in 2022, which may be due to changing thermal conditions of the X-ray emitting CSM and/or the start of reverse shock interactions with the Fe-ejecta.

SNR IC443 - Morphology and kinematics of the "Jellyfish nebula" in three dimensions

Oral Talk

Sophia Derlopa, Panos Boumis, and Stavros Akras

IAASARS, National Observatory of Athens, Greece

Abstract

The complexity that Supernova Remnants (SNRs) usually illustrate denotes a very active past from the time of their explosion up to the time of their current observation. The decoding of this activity which is embedded into their properties, is the key in order to trace back to the formation history of a SNR, contributing by this way to the stellar evolution models. A powerful tool for this probing, is the reconstruction of the 3D Morpho-kinematic (MK) modelling of a SNR, by the use of SHAPE software, which provides both the morphology and the velocity field of the object in three dimensions. This has already been proved in the case of the very complicated SNR VRO 42.05.01, which was the first SNR ever used as a case study in a 3D MK model. Following that, we moved on to an even more complex case of a SNR, as is the case of IC443 (G189.+3.0). IC443 is a very well-studied Galactic SNR of the later evolutionary stage, also known as the "Jellyfish nebula". Its complex morphology seems to consist of two basic shells of different radii, both composed of bright filamentary structures. It is surrounded by atomic and molecular clouds, while its hosted pulsar star produces pulsar winds resulting in slow and fast shock waves propagating through its entire area. For the 3D modelling, we obtained wide-field imaging data in the optical, along with 26 echelle spectra in total, the latter covering the whole area of the nebula. In the contributed talk, the preliminary results of the model will be presented. Regarding its kinematics, the model revealed a highly complicated velocity field of IC443, both in its main shells, with velocities up to $\sim$250 km s^{-1}. On the other hand, with respect to its morphology, "hidden" bubbles seem to be scattered at its interior, which confirms that IC443 indeed consists of structural irregularities.

Toward understanding the progenitor channels to SNe Ibn/Icn: X-ray modeling of their SN-CSM interaction

Oral Talk

Yusuke Inoue and Keiichi Maeda

Kyoto University, Japan

Abstract

Type Ibn/Icn supernovae (SNe Ibn/Icn), which are characterized by strong and narrow helium and carbon line originated in hydrogen-poor dense circumstellar medium (CSM), provide new insights into the final evolution of massive stars. Their light curves (LCs) are explained by the collision between the ejecta of the SN explosion (ejecta) and the CSM (SN-CSM interaction). SNe Ibn/Icn are thus expected to emit strong X-rays from the shocked region, as was demonstrated by soft X-ray ($<$ 10 keV) from Type Ibn SN2006jc. The modeling effort of the X-ray emission for SNe Ibn/Icn is very limited so far, despite the expected rapid increase of observational samples in a coming decade. In the present study, we provide broad-band X-ray LC predictions for SNe Ibn/Icn. By a numerical approach taking into account the rapid cooling of thermal electrons due to the high CSM density, we find that the soft X-ray LC provides information about CSM composition, while the hard X-ray LC could robustly determine physical properties such as the CSM density, explosion energy, and ejecta mass. In addition, considering photoionization changes in unshocked CSM, we find that there may be some SNe Ibn/Icn which exhibit a double-peaked LC in soft X-ray even for a single power-law CSM distribution. Applying our model to the soft X-ray LC of SN2006jc, we find that it can be explained by carbon and oxygen-rich CSM. We conclude that broad-band X-ray observation is crucial to robustly reveal the CSM and explosion properties. We also discuss detectability and observational strategy, with which the currently operating telescopes such as NuSTAR, Chandra, and Swift can offer an irreplaceable opportunity to explore these enigmatic rapid transients and their still-unclarified progenitor channel(s).

Multiwavelength Observations of Old Stripped-Envelope Supernovae

Oral Talk

Ryan Chornock

UC Berkeley, USA

Abstract

While most supernovae fade from detectability within a year after the explosion, patient long-term monitoring can reveal surprises. Our group previously identified a sample of supernovae with unusual luminous radio emission around a decade after the explosion using the VLA Sky Survey. Intriguingly, these are primarily from explosions of hydrogen-stripped stars. I will provide an update on our ongoing work to characterize this sample across the electromagnetic spectrum from the radio (VLA) and optical (deep Keck spectroscopy) to the X-rays (Chandra). The radio emission can have a variety of causes, from H-rich circumstellar interaction at large radii (similar to the exceptional SN 2014C), to objects that may show signs of the emergence of pulsar wind nebulae. These observations help to bridge the gap between the SN at early times and the future remnant.

Polarization signature showing an elevated and asymmetric mass loss from the progenitor of SN2023ixf prior to the explosion

Oral Talk

Manisha Shrestha

University of Arizona, USA

Abstract

The progenitors of hydrogen-rich supernovae are red supergiants. However, the mass loss in the final years before a red supergiant's supernova explosion is not well understood and is difficult to observe directly. Interestingly, the circumstellar material (CSM) created by this mass loss can have an impact on the light curve, spectra, and polarization. In particular, polarimetric observations can constrain CSM geometry which cannot be resolved using traditional astronomical techniques. With these observations, we are starting to explore the structure and element distribution of these explosions shedding light on the mass loss of red supergiants in their final phase. In this talk, I will discuss our polarimetry data analysis of SN2023ixf, the closest supernova in a decade, spanning from 2 to 100 days after its discovery. We detect significant intrinsic polarization during the light curve rise, a decrease in polarization during the plateau phase, and a rise when the light curve falls from the plateau, about 100 days after the explosion. Spectropolarimetry data of H alpha shows that the outer regions of the supernova ejecta and CSM are aligned. Whereas the line polarization around the He II line shows a position angle shift from the continuum indicating a possibility of a different location for He II with respect to continuum emission. This analysis indicates an aspherical CSM and ejecta for SN2023ixf signifying an elevated and asymmetrical mass loss from the progenitor right before the supernova explosion. This study shows the power of the polarization technique in deciphering the mass loss process.

On the interaction of supernova remnants with their circumstellar medium: evolution, properties, and progenitors' imprints

Invited Talk

Alexandros Chiotellis

National Observatory of Athens, Greece

Abstract

Supernova remnants (SNRs) are the aftermath of supernova explosions, resulting from the interaction of the stellar ejecta with the medium that surrounds the explosion center. In most cases, the ambient medium properties deviate substantially from homogeneity and differ dramatically from the local interstellar medium properties, due to the mass outflows of the stellar progenitor system during its pre-supernova evolution. The interaction of the supernova ejecta with the sculptured circumstellar structures alters the evolution of the SNR and the effects of this interaction are reflected in the morphology, kinematics, and emission properties of the resulting remnant. Thus, by deciphering the properties of SNRs through targeted observations and detailed modeling we are able to map the structure and geometry of the surrounding circumstellar medium through which we get crucial insights into the nature and evolution of the progenitor system. In this review talk, we present the dominant processes that govern the interaction of the supernova ejecta with the surrounding circumstellar medium, we discuss the formation mechanisms behind frequently met structures in SNRs (e.g. bow-shocks, antisymmetric lobes, tori, equatorial belts, etc.) and we aim to provide directs links between the properties of the SNRs and the nature and evolution of their parent stellar systems.

Broadband non-thermal emission as an effective probe of progenitor origins of core-collapse supernova remnants

Oral Talk

Herman Shiu-Hang Lee, Haruo Yasuda, and Keiichi Maeda

Department of Astronomy, Kyoto University, Japan

Abstract

While the task of linking supernova remnants (SNRs) to their progenitor origins has mostly been relying on their thermal X-ray emission such as extracting the elemental abundance patterns in their ejecta, the connection between the nature of the exploded stars and the non-thermal emission seen in their remnants hundreds or thousands of years after the explosions has not been explored in depth so far. We use hydrodynamic simulations to model the long-term evolution of SNR non-thermal emission and search for their possible correlations with the explosion properties and circumstellar environments associated with specific types of core-collapse supernovae (CCSNe). We have discovered a highly characteristic relation between the originating SN types and the broadband non-thermal light curve and spectral evolution. Its implication for understanding the SNR population and the interpretation of the observed diversity in the gamma-ray spectra of SNRs at different ages is profound.

Radiative transfer models for 1-10yr-old supernovae: influence of interaction power, magnetar power, and dust.

Oral Talk

Luc Dessart

Institut d'Astrophysique de Paris, CNRS, France

Abstract

In this talk, I will present recent developments for the modeling of supernovae beyond one-year post-explosion with CMFGEN. While the exponential decline of decay power and gamma-ray escape impact adversely the SN brightness, interaction with circumstellar material or energy injection from the compact remnant can induce a large SN luminosity for many years and help cover the transition to the supernova remnant stage. I will present results for such phenomena in events analogous to the Type IIn SN 1998S or the Type IIb SN 1993J. I will also present preliminary results on the impact of dust formation in such supernovae.

Session 2.

SNe and SNRs with Circumstellar Interactions – Posters

Probing supernova remnant VRO 42.05.01's progenitor properties with IRAM 30m observations

Poster

Maria Arias

Leiden Observatory, The Netherlands

Abstract

VRO 42.05.01 is a mixed-morphology supernova remnant (SNR) whose unusual 'shell and wing' shape has been the subject of much speculation, and attributed to an ambient density discontinuity. We performed millimeter observations with the IRAM 30m telescope and mapped the molecular gas surrounding the remnant, with the aim of understanding the dense material's role in determining the shape of the source. We unexpectedly found evidence of the mass-loss history of the progenitor star before the explosion imprinted on the molecular material: sweeps in velocity space, and shocked gas with different characteristics (in terms of excitation ratios and velocity spreads) than those outlining the region of interaction between the SN blast wave and the molecular gas. The regions of molecular cloud/stellar wind interactions are consistent with an equatorially enhanced wind. We propose that the star's pre-SN properties, rather than the ambient medium, are responsible for its unusual morphology. This work showcases the possibility of probing the properties of a SNR progenitor via its imprint on the ambient dense ISM.

A multi-wavelength autopsy of a young interacting supernova to unveil its progenitor

Poster

Raphael Baer-Way[1], Poonam Chandra[2], Maryam Modjaz[1], Sahana Kumar[1], Craig Pellegrino[1]

[1]University of Virginia, USA
[2]National Radio Astronomy Observatory, USA

Abstract

While interacting supernovae are some of the most luminous supernovae across the electromagnetic spectrum extending to late times, their origins are still not well-constrained. In order to fully grasp their progenitor characteristics through their mass-loss history, multi-wavelength observations are vital. Here we present such observations of the interacting type IIn supernova 2020ywx spanning from the low frequency radio bands to the high frequency X-ray bands. SN 2020ywx is remarkable for its very high X-ray luminosity (second most luminous X-ray supernova of all time) and for the extremely slow linear decline of the optical lightcurve (< 0.003 mag/day) suggestive of sustained interaction with a highly dense H-rich CSM shell. Using multi-epoch X-ray, optical, and radio spectra and lightcurves, we derive three independent estimates for the progenitors mass-loss rate which are relatively consistent across wavelengths at ~ 0.01 $M_\odot$ yr $^{-1}$. Given the derived high steady mass loss over centuries pre-explosion, we explore progenitor possibilities including pulsational instabilities and enhanced binary interaction in the lead up to the explosion of 2020ywx. Given the hydrogen-rich CSM and the duration of mass loss calculated, we suggest that binary interaction is the most likely progenitor channel. Furthermore, we explore the blueshifting of the optical emission lines, which in conjunction with the blackbody continuum of the NIR spectra suggests that 2020ywx has most likely started forming dust in the dense shell between its forward and reverse shock. Based on the similarities and differences across wavelengths with other prototypical type IIns (i.e. 2010jl), we further examine how 2020ywx fits into the type IIn continuum.

Radiative Transfer Modeling of Astrophysical Transients Powered by Circumstellar Interaction

Poster

Manos Chatzopoulos and G. Wagle

Louisiana State University, USA

Abstract

In this presentation, I will introduce 'SuperLite' a novel open-source Monte Carlo radiation transport code specifically crafted for simulating synthetic spectra of astrophysical transients influenced by circumstellar interactions, SuperLite makes use of more generalized radiation transport physics that enables it to treat high-velocity shocked outflows using advanced Monte Carlo methods and multi-group structured opacity computations. The first public release of SuperLite offers the capacity for efficient post-processing of hydrodynamic profiles, which allows for the computation of high-fidelity spectroscopic models. These models are vital for the comparative analysis of various transient events, encompassing phenomena like superluminous supernovae, pulsational pair-instability supernovae, and other unique transients such as FBOTs and FELTs. In this session, we will delve into the methodologies integrated into SuperLite, showcasing its comparative edge over renowned radiative transport codes like SuperNu and CMFGEN. We will demonstrate how SuperLite not only meets but excels in standard Monte Carlo radiation transport benchmarks and its ability to accurately replicate spectra of common supernova types such as Type Ia, Type IIP, but also those of interacting SN Type IIn.

Multidimensional Radiation Hydrodynamics Simulations of Supernova 1987a Shock Breakout

Poster

Wun-Yi Chen, Ken Chen, Masaomi Ono

ASIAA/NTU, Taiwan

Abstract

Shock breakout is the first electromagnetic signal from supernovae (SNe), which contains important information on the explosion energy and the size and chemical composition of the progenitor star. This paper presents the first two-dimensional (2D) multi-wavelength radiation hydrodynamics simulations of SN 1987A shock breakout by using the CASTRO code with the opacity table, OPAL, considering eight photon groups from infrared to X-ray. To investigate the impact of the pre-supernova environment of SN 1987A, we consider three possible cases of circumstellar medium (CSM) environments: only a steady wind; an eruptive mass loss; and the existence of a companion star. In sum, the resulting breakout light curve has an hour duration and its peak luminosity of $\sim 6{\times}10^{46}$ erg s^{-1} following efficient post-breakout X-ray cooling of $\sim$ 3.5 mag hour^{-1}. The dominant band transits to UV after around 3 hours of shock breakout and its luminosity has a decay rate of $\sim$ 1.5 mag hour^{-1} that agrees well with the observed shock breakout tail. The detailed features of breakout emission are sensitive to the pre-explosion environment. Our 2D simulations also demonstrate the importance of post-breakout mixing and its impacts on shock dynamics and radiation emission. The mixing driven by the shock breakout may lead to a global asymmetry of SN ejecta and affect its later supernova remnant formation.

2D Rad-Hydro Shock Breakout Simulations on RSG with CSM

Poster

Wun-Yi Chen, Ken Chen, Masaomi Ono and Po-Sheng Ou

ASIAA/NTU, Taiwan

Abstract

We present 2D radiation shock breakout of Red Super Giant progenitors (RSG) using CASTRO with OPAL opacity table. Shock breakout signals that present longer duration than expected are deemed to result from the dense circumstellar medium (CSM) pre-explosion environments. A thorough study of the radiation-mediated shock interactions with swapped materials during the opacity variation epoch for shock breakout events should be considered, including fluid instabilities forming nonlinear structures after supernova explosions. This can reveal the late-time evolution of progenitor stars. We showcase our capacity to model a scenario involving a 20 $M_\odot$ RSG with a steady mass loss rate of $\dot{M}$=6.46x10^{-6} $M_\odot$ yr^{-1} for the CSM profile. The influence of multidimensional evolution in this context notably extends the shock's duration and introduces essential considerations for cooling criteria. These aspects gain particular significance when investigating the mass loss history within the context of a delayed shock breakout event in a dense CSM. As a result, it becomes imperative to perform calculations that accurately account for the real-space expansion of shells. In our simulation, we achieve a swift upsurge in luminosity within a span of just 5 days, accompanied by a shift towards bluer frequencies, registering a rate of $\dot{L}$=2.4 mag day^{-1}. In the ensuing plateau phase, which endures for approximately 20-30 days and maintains a luminosity of -17.6 mag, the rate of change is measured at $\dot{L}$=0.0276 mag day^{-1}. 2D simulations show significance difference in shock breakout duration and distribution of peak luminosity across angles of observations, we emphasize the multi-dimensional effects and future study based on shock breakout should consider the effects to guarantee correct interpretation of CSM profiles.

Clues (and conundrums) from the circumstellar media around extreme extragalactic transients

Poster

Ashley Chrimes

ESA/ESTEC

Abstract

From synchtron-emitting blast-wave and afterglow modelling, it is possible to infer the circumstellar density profile around the progenitors of extragalactic explosions including supernova, luminous fast blue optical transients (LFBOTs, or Cow-like transients), and gamma-ray bursts (GRBs). LFBOTs and some long-duration GRBs appear to have dense circumstellar media with wind-like profiles. In this poster, I discuss how the circumstellar medium around LFBOTs is providing valuable insight into their progenitors (with focus on the recent event AT2023fhn). Meanwhile, the prevalence of ISM-like, flat density profiles at low radius around many long-duration GRBs - thought primarily to have massive star progenitors - is puzzling. Possible interpretations are discussed.

Type Ia Supernova Remnants in Different Circumstellar Environments

Poster

Travis Court[1], Carles Badenes[1], Shiu-Hang Lee / Kyoto University[2] and Dan Patnaude[3]

[1] University of Pittsburgh, USA
[2] Kyoto University, Japan
[3] Harvard Center for Astrophysics, USA

Abstract

Different scenarios for the evolution of Type Ia supernova progenitors make radically different predictions about the pre-explosion mass loss, resulting in a wide array of possible structures for the circumstellar material. This circumstellar material leaves a strong imprint on the bulk dynamics (radius, velocity, and ionization timescale) of X-ray bright supernova remnants (SNRs). I will present results from an ongoing effort to explore the parameter space of circumstellar interaction in Type Ia supernovae using an extensive grid of SNR models and synthetic X-ray spectra. Among the scenarios explored in our grid are isotropic winds of varying speeds and mass loss rates, bipolar cocoons from common envelope episodes, and low-density cavities of various sizes. I will focus on what areas of this large parameter space are ruled out by current X-ray observations of SNRs such as, higher mass loss rates with slow outflows.

An XMM-Newton study of several nonradiative filaments in the northeastern rim of the Cygnus Loop

Poster

Jasmina Horvat and D. Onic

Department of Astronomy, Faculty of Mathematics, University of Belgrade, Serbia

Abstract

We present the results from spectral analysis of several nonradiative filaments in the northeastern rim of the Cygnus Loop supernova remnant (SNR). For this purpose, we use the XMM-Newton observation, Obs. ID 0741820101. Particular regions represent a very interesting part of the SNR where possible charge-exchange line emission is proposed to explain the so-called 'enhanced' abundances problem. A proper background treatment is essential as possible solar wind charge exchange emission may affect the results.

The thermal relaxation process in collisionless shock of SN1006

Poster

Masahiro Ichihashi[1], Aya Bamba[1], Yuichi Kato[1], Satoru Katsuda[2], Hiromasa Suzuki[3], Tomoaki Kasuga[1], Hirokazu Odaka[4] and Kazuhiro Nakazawa[5]

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Abstract

There are a lot of ubiquitous, but unexplained phenomena in the physics near the shock. One of the examples is the shock heating and thermal relaxation process after the collisionless shock. The plasma density in the universe is quite low, so particle collision rarely happens. On the other hand, the temperature of each particle just after the collisionless shock heating is independent of the mass of each particle, so the relaxation process occurs after the shock heating. These processes are considered to progress via the electromagnetic field, but the detail of them is not well understood. For the understanding of the relaxation process just after the shock, we analyzed the northwestern region of SN1006 taken by the data of Chandra, whose spatial resolution is highest in the X-ray satellites. We divided the region just after the shock into four layers with a thickness of 15 arcsec (or 0.16 pc) each, and fit each spectrum by a non-equilibrium ionization collisional plasma model. As a result, the electron temperature was found to increase downstream from $0.52 - 0.62$ keV to $0.82 - 0.95$ keV on a length scale of 60 arcsec (or 0.64 pc). We compared this electron temperature to the Coulomb scattering model and found that the electron temperature in the inner region, where a long time has passed since the shock wave passed through, is lower than the prediction of the Coulomb scattering model. This is considered as the existence of the energy leakage from our observation region. To estimate the amount of energy leakage, we need to understand the temperature of ions, which have most of the energy just after the shock. We cannot do that due to the lack of energy resolution of Chandra. We expect future analysis by using the X-ray satellite with high energy and spatial resolution such as Athena.

Final Moments: Observational Properties and Physical Modeling of "Flash Spectroscopy" Supernovae

Poster

Wynn Jacobson-Galan

UC Berkeley, USA

Abstract

There is now an amalgam of observational evidence that massive stars undergo enhanced and/or eruptive mass-loss in their final years before explosion. In this talk, I will present multi-wavelength observations of > 40 type II SNe whose very early-time ("flash") spectra showed transient, narrow emission lines from shock interaction with confined circumstellar material (CSM) around their RSG progenitor stars prior to shock breakout. I will discuss the observational properties of this "flash spectroscopy" SN sample, the largest to date, and how these objects compare to normal SNe II that arise from stars without significant mass-loss. This sample also includes the CSM-interacting type II SN 2023ixf, the closest and brightest SN of the decade, which was discovered within an hour of explosion. Lastly, I will present modeling of these SNe using non-LTE radiative transfer code CMFGEN, which allowed for the best constraints to date to be made on the CSM structure and mass-loss histories of the RSG progenitors responsible for these fascinating events.

Investigation into SNR-accelerated CRs at the prospect of future MeV gamma-ray detectors

Poster

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Abstract

Line emission and continuum at MeV band can provide us essential information concerning the acceleration and confinement of cosmic ray (CR) in SNRs. MeV nuclear de-excitation lines (at the energy range of ∼1–10 MeV) serve as a unique tool to study low-energy CRs, containing both spectral and elemental information of the interacting material. Meanwhile, the distinguish of pion-bump structure and the unavoidable bremsstrahlung emissions from secondary and primary electrons in the energy range between 10–100 MeV can provide the decisive evidence for the acceleration of hadronic CR in SNRs and important information of confinement of high-energy particles. Here, we took the young SNR Cas A as a representative, estimated the possible nuclear de-excitation lines from Cas A. Given different CR spectral shapes and interacting materials, we found the predicted fluxes of strong narrow line emissions from the remnant are highly model-dependent. Next, we took the mid-aged supernova remnants W44 as an example and studied the predicted gamma-ray spectrum from the SNR assuming both hadronic or leptonic origin. We also discussed the detection probability of future MeV missions on these emissions and possible implications.

Light curves of multiple ejecta-circumstellar medium interactions

Poster

Liang-Duan Liu

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Abstract

Interacting supernovae (SNe) of types IIn and Ibn, distinguished by their narrow emission lines, have consistently represented perplexing and unresolved phenomena within the domain of supernova physics. Observational data indicate that certain light curves (LCs) of these supernovae manifest distinctive post-peak fluctuations. We propose a model founded on the premise of interaction between supernova ejecta and the circumstellar medium, integrating the concept of multiple shells or winds, to elucidate these anomalous LC behaviors. An examination of these fluctuating light curves of SNe could shed light on their intrinsic properties and offer insights into the mass-loss history of their progenitor stars, enhancing our understanding of stellar evolution.

How do supernova remnants cool? Morphology and optical emission lines

Poster

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Abstract

Observed supernova remnants (SNRs) often interact with dense nearby molecular clouds. In these high-density environments, radiative losses are significant and can be observed in forbidden lines at optical wavelengths, especially for evolved SNRs. We developed a post-processing module for the 3D (magneto)hydrodynamic FLASH code. This module uses the updated collision data from the MAPPINGS V code to produce realistic emission maps of simulated SNRs in optical emission lines ([O III], [N II], [S II], Hα, Hβ). Our shock detection scheme shows that [S II] and [N II] emissions arise from the thin shell surrounding the SNR, while [O III], Hα, and Hβ originate from the volume-filling hot gas inside the SNR bubble. We also analysed a dataset of 22 simulations to determine whether SNR at different positions within a molecular cloud (+ with/without magnetic fields) can be distinguished based on their optical emission using unsupervised machine learning (e.g., principal component analysis (PCA), and k-means clustering). We find that the presence or absence of magnetic fields has no statistically significant effect on optical line emission. However, the ambient density distribution at the SNR site changes the SNR's entire evolution and morphology.

Infrared emission of supernova remnants in the Small Magellanic Cloud

Poster

Mikako Matsuura

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Abstract

With the entire Small Magellanic Cloud (SMC) mapped by the Spitzer Space Telescope and Herschel Space Observatory, we were able to search 8-250 micron images in order to identify infrared (IR) emission associated with SMC supernova remnants (SNRs). A valid detection had to correspond with known X-ray, H alpha, and radio emission from the SNRs. From the 24 known SNRs, we made five positive detections with another five possible detections. Two detections are associated with pulsars or pulsar wind nebula, and another three detections are part of the extended nebulous emission from the SNRs. We modelled dust emission where fast-moving electrons are predicted to collide and heat dust grains which then radiate in IR. With known distance (62 kpc), measured SNR sizes, electron densities, and temperatures from X-ray emission as well as hydrogen densities, dust emission in SMC SNRs is predicted. If the higher range of hydrogen and electron densities were to be accepted, we would expect almost all SMC SNRs to be detected in the IR, at least at 24 micron, but the actual detection rate is only 25 per cent. One possible and common explanation for this discrepancy is that small grains have been destroyed by the SNRs shockwave. However, within the uncertainties of hydrogen and electron densities, we find that IR dust emission can be explained reasonably well, without invoking dust destruction. There is no conclusive evidence that SNRs destroy swept-up ISM dust within the uncertainties.

Spectral Analysis of Chandra data on selected regions of the Supernova Remnant Cassiopeia A

Poster

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Abstract

Cas A is one of the youngest known Supernova Remnants (SNRs) in the Milky Way and is one of the brightest and most studied SNRs. X-ray telescopes, such as the Chandra X-ray Observatory, have provided detailed images of the structure of the remnant, revealing its complex nature. The X-ray emission of Cas A is dominated by two components, the shocked stellar fragments of the progenitor star (the ejecta) and the synchrotron radiation emitted by energetic electrons accelerated at the shock front. The aim of this study is to characterize the physical and chemical observables of the X-ray emitting plasma through a spatially resolved spectral analysis. This technique also allows us to estimate the electron density and the shock velocity in different regions of the SNR. Thus, this study provides information on the nature of the plasma, on the non-thermal and thermal fluxes, and on the contribution of the ISM/CSM in which the SNR expands. The analysis of various spectral parameters has revealed several differences between the north-eastern and south-western regions. These differences suggest the presence of distinct physical conditions and properties within these regions. South-west regions are cooler and denser while there is a hotter plasma in the north-east regions. These findings strongly imply the existence of a hotter and more ionized plasma in the north-eastern regions, attributed to the presence of a rapidly expanding shock wave, specifically the forward shock. The analysis of the chemical abundances across all the regions underscores a remarkable similarity to solar abundances, indicating that the majority of the analyzed Cas A regions are primarily composed of shocked ISM or CSM material.

Molecular Clouds associated with middle-aged gamma-ray Supernova Remnants W41 and G22.7–0.2

Poster

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Abstract

The origin of cosmic rays (CRs), mainly composed of relativistic protons, is one of the long-standing key questions in modern astrophysics. Supernova remnants (SNRs) are thought to be promising sites for the acceleration of CRs below ∼3 PeV via diffusive shock acceleration (DSA, e.g., Bell 1978; Blandford & Ostriker 1978). From previous studies, a relation between the age of the SNR and the total energy of the accelerated CRs, W_{p}, has been presented for 14 gamma-ray SNRs (Sano et al. 2021ab, 2022; Aruga et al. 2022). Young SNRs $<$ 6 kyr show a positive correlation, while middle-aged SNRs (age $>$ 8 kyr) exhibit a negative correlation. These authors argued that the latter correlation is likely caused by cosmic-ray escape from the SNR. The relation between age and W_{p} is crucial for understanding the mechanisms of cosmic-ray acceleration and escape in the SNR. However, the studied samples lack SNRs with ages greater than ∼20 kyr. One of the main current challenges is to establish age-W_{p} relation for Galactic SNRs with various ages. We present a study of gamma-ray SNRs W41 and G22.7–0.2 with the ages of 45 kyr and 20 kyr, respectively (e.g., Stafford et al. 2019). We have identified the molecular clouds associated with the SNRs using the CO datasets of FUGIN (FOREST Unbiased Galactic plane Imaging survey with the Nobeyama 45-m telescope, Umemoto et al. 2017). In addition, we newly found good spatial correspondence between the gamma rays and molecular clouds. We then derived $W_m athrmp$ of W41 and G22.7–0.2 to be $\sim(3.2\pm0.2)\times10^{47}$ erg and $\sim(7.5\pm0.8)\times10^{48}$ erg, respectively. The age-W_{p} relation of these SNRs was found to be roughly consistent with the trends shown in previous studies. In the present poster, we discuss cosmic-ray proton acceleration in SNRs, and the spatial distribution of the molecular clouds associated with W41 and G22.7–0.2.

How can circumstellar interaction explain the special light curve features of Type Ib/c supernovae?

Poster

Andrea Nagy, Zsófia Réka Bodola

University of Szeged, Hungary

Abstract

The evolution and the surrounding of stripped-envelope supernova progenitors could significantly modify the overall light curve features of the explosions. To better understand this phenomenon, we assume a specific circumstellar configuration. Namely, the circumstellar matter is generated by an extreme episodic mass-loss event days before the supernova explosion that may explain the controversies related to the general light curve features of Type Ib/c supernovae. To test the effect of such a circumstellar regime, we computed the bolometric light curve of both interacting single- and binary progenitor models via hydrodynamic simulations. As a result, we found that a close, dense circumstellar matter may be responsible for the unique light curve features (re-brightening, double peak) of some stripped-envelope supernovae. Moreover, the light curve shape of stripped-envelope supernovae could also indicate that the cataclysmic death of the massive star happened in a binary system or was related to the explosion of a single star.

Constraining the CSM structure and progenitor mass-loss history of SN 2014C through 3D hydrodynamic modeling

Poster

Salvatore Orlando[1], Emanuele Greco[1], Ryosuke Hirai[2], Tomoki Matsuoka[3], Marco Miceli[4], Shigheiro Nagataki[5], Masaomi On[3], Ke-Jung Chen[3], Dan Milisavljevic[6], Daniel Patnaude[7], Fabrizio Bocchino[1]

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Abstract

The remnants of core-collapse supernovae (SNe) can contain valuable information about the SN engine and the structure of the inhomogeneous ambient medium through which they expand. Analyzing observations of these remnants can yield crucial insights into the SN event itself and the progenitor stellar system. Particularly intriguing are SNe where the expelled material interacts significantly with their surroundings during the early phases of evolution. Such interactions can provide valuable insights into mass-loss events that occurred centuries to millennia before the SN explosion, thus allowing to shed light on the terminal stages of massive star evolution and the elusive mechanisms driving their mass loss. Here, we present 3D hydrodynamical modeling aimed at describing the evolution of SN 2014c, a well-studied interacting SN observed in the X-ray band with Chandra and NuSTAR. The model describes the evolution of the progenitor star, the SN, and the SN remnant interacting with a dense and inhomogeneous circumstellar medium (CSM). By comparing the model results with X-ray observations, we were able to constrain the structure and geometry of the CSM and the mass-loss history of the progenitor stellar system. Moreover, we were able to disentangle the respective contributions to multi-epoch X-ray spectra from the shocked CSM and the shocked ejecta.

A possible circumstellar interaction of SN2004gq

Poster

Boróka Hanga Pál, Andrea P. Nagy, Tamás Szalai

University of Szeged, Hungary

Abstract

Studying the interaction between the supernova ejecta and the circumstellar medium (CSM) plays a major role in understanding better the stripped-envelope supernovae. Moreover, it also provides an opportunity to learn more about shock physics connects to both thermal and non-thermal processes, including relativistic particle acceleration and radiation processes. Therefore, we aim to estimate one of the most crucial characteristics of the pre-supernova evolution, the average mass-loss rate. This parameter is significant to figure out the structure of the CSM as well as determining the physical configuration of the progenitor star. For that, we choose the Type Ib supernova, SN2004gq and systematically analyze its radio- and quasi-bolometric light curves. At radio wavelengths, we fit the data with an analytical model created by Weiler (2007), that includes both non-thermal synchrotron self-absorption and thermal free-free absorption. After determining the model parameters, we were able to estimate the average mass-loss rate of the progenitor. Besides, we fit the quasi-bolometric light curve of this supernova with our semi-analytic model taking into account the CSM interaction as an extra energy source. It was also possible to calculate the average mass-loss rate from this fitting. Comparing the results from the two different wavelengths, we could receive an insight into what could have happened during the pre-explosion evolution of SN2004gq.

Density and magnetic field gradients in Tycho SNR

Poster

Oleh Petruk[1,2], T. Kuzyo[2], M. Patrii[3], M. Miceli[4], S. Orlando[1], F. Bocchino[1], L. Chomiuk[5] and M. Arias[6]

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Abstract

Utilizing the radio and X-ray surface brightness maps of the Tycho SNR as well as properties of emission in these bands, we obtained the images for density and magnetic field strength across the remnant. Our analysis reveals the presence of a density gradient in the North-West direction. The gradient of magnetic field strength is parallel to the plane of the Galaxy and points toward the East. By using these maps, we further derived the spatial distributions of both the cut-off frequency and maximum energy of electrons in the Tycho SNR, and commented on gamma-ray emission from Tycho SNR.

Interaction of a Supernova Remnant with background interstellar turbulence

Poster

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Abstract

Supernovae explosions (SNe) are among the most energetic events in the Universe. It is an instantaneous release of energy of about 10^{51} erg, associated to the catastrophic collapse of a massive star or due to a runaway nuclear burning on the surface of a white dwarf. After the explosion, the material ejected by the Supernova expands throughout the interstellar medium (ISM) forming what is called Supernova Remnant (SNR). Shocks associated with the expanding SNR are the sources of Galactic cosmic rays, that can reach energy of the PeV order. In these processes, a key role is played by the magnetic field. It is known that the ISM is turbulent with a magnetic field field observed of about a few μG, made by a uniform and a fluctuating component. During the expansion of the SNR shock, it interacts with a turbulent environment, and as a consequence the surface of the shock can be distorted and the level of fluctuations can increase. In this work, we use numerical simulations in order to reproduce the evolution of a SNR. We use the MHD PLUTO code in order to mimic the evolution of the blast wave associated with the SNR. We make a parametric study varying the level of density and magnetic fluctuations, with the aim of understanding what are the best parameter values able to reproduce real observations. Indeed, a preliminary comparison with Chandra observations will also be presented.

Probe charge exchange and resonant scattering in Magellanic Cloud supernova remnants with spatially-resolved high-resolution X-ray spectroscopic study of oxygen lines

Poster

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Abstract

Charge exchange (CX) and resonant scattering (RS) can play important roles in constituting and modifying the X-ray spectra of supernova remnants (SNRs). Oxygen lines provide a unique perspective to constraint the CX and RS effects in SNRs. Based on XMM-Newton RGS observations, we found unusually high O VII G-ratios in four Magellanic Cloud SNRs (i.e., N49, DEM L 71, J0453-6829, and J0534-6955). We constructed the exposure-corrected dispersion images of O VII lines for these SNRs and further investigated the spatial variations of the G-ratio across the remnants. For all the four remnants, we found significant spatial variation of the G-ratio. By comparing the G-ratio variations with the distributions of the shocked hot plasma (probing by X-ray emission measure maps) and the ambient neutral gas (probing by H I and Hα images), we discussed the possibility of RS and CX as the origin of the high G-ratios.

Role of reflected shocks in particle acceleration in supernova remnants

Poster

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Abstract

Majority of supernova remnants (SNRs) originate in core-collapse events and are expected to expand into a complex environment of the stellar wind bubble blown up by their progenitor stars, where forward shock might interact with various density inhomogeneities. Such interaction would cause formation of a set of fast reflected shocks propagating back and forth between the forward and reverse shocks of the remnant. Current investigations of particle acceleration in SNRs are usually limited to forward and reverse shocks ignoring the complexity of the hydrodynamic picture. Although for most SNRs the observed shell-like morphology generally agrees with an idea that high energy particles originate predominantly from the forward shock, precise spatially resolved measurements do not always agree with a simplified picture giving rise to alternative ideas such as interaction with dense cloudlets. This work investigates the impact of the interaction of reflected shocks with forwards and reverse shocks of an SNR on the particle acceleration in the source and examines observational signatures that could potentially arise from such interactions.

Multi-dimensional simulations of interaction-powered supernovae

Poster

Akihiro Suzuki

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Abstract

Recent optical supernova surveys continue to discover populations of transients powered by the collision of the ejected materials with circum-stellar materials (CSMs). Nowadays, it has turned out that any spectral type of supernovae (SNe; both core-collapse and thermonuclear) can be interaction-powered or exhibit some spectral signatures of CSM interaction. Even CCSNe that look normal can also be powered by CSM interaction in their early stage, as is clearly observed in the recent nearby SN 2023ixf. Such CSMs are found in the vicinity of SN progenitors and therefore indicate their origin closely related to still mysterious mass-loss processes immediately before the explosion. Then, the central question is how exactly such CSMs could be created around exploding stars. Tackling this important problem requires detailed modelings of electromagnetic signals from interaction-powered SNe based on radiation-hydrodynamic simulations and comparisons with observations. In this presentation, I introduce our 2D radiation-hydrodynamic models of SN ejecta colliding with spherical and aspherical CSMs. SN ejecta interacting with aspherical CSMs (e.g., disk-like) produces a variety of light curves depending on the viewing angle, which can be a powerful probe of CSM origins. I discuss what we can learn from multi-D modelings of interaction-powered transients.

Global and Rapid Deceleration of X-Ray Knots and Rims of RCW 103

Poster

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Abstract

We report on a proper motion measurement of X-ray knots and rims of the magnetar-hosting supernova remnant RCW 103. Chandra data obtained in three epochs, 1999, 2010, and 2016 are used. We find a global deceleration of 12 knots and rims both in northern and southern regions within the last ~ 24 yrs, even though its age is thought to be larger than 2 kyr. Some of them even changed their moving directions from outward ($\sim 1,000$ km s^{-1}) to inward ($\sim -2,000$ km s^{-1}). The energy spectra extracted from the decelerating regions are well explained with a solar-abundance thermal plasma model. Our findings can be explained with a collision with a jump in density by a factor of $\gtrsim 40$ both in the northern and southern edges of the remnant, although the remnant may still be expanding in the wind-blown cavity according to its inferred progenitor properties.

Shocked Molecular Clouds in the LMC SNR N132D Revealed by ALMA ACA

Poster

Kisetsu Tsuge[1], Hidetoshi Sano[1], Rami Alsaberi[2], Aya Bamba[3], Miroslav Filipovic[2], Yasuo Fukui[4], Charles Law[5], Norikazu Mizuno[6], Toshikazu Onishi[7], Paul Plucinsky[8], Gavin Rowell[9], Manami Sasaki[10], Piyush Sharda[11], Hiromasa Suzuki[12], Kengo Tachihara[4], Kazuki Tokuda[6] and Yumiko Yamane[4]

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Abstract

Supernova remnants (SNRs) play a crucial role in galaxy evolution due to their energetic shocks and metal enrichment. Especially, shock-cloud interactions are highly related not only to cosmic-ray acceleration but also to star formation rate (e.g., Kortgen et al. 2016). We aim to investigate the universality of physical processes resulting from shock-cloud interactions. SNR N132D is the most suitable target for investigating various shock-cloud interactions. N132D is the most luminous SNR in the local group and is located at the Large Magellanic Cloud (LMC). A well-known distance and little contamination made it easy to accurately estimate the physical properties of molecular clouds associated with N132D. In the present study, we analyzed the latest ^{12}CO(3-2) data obtained with ALMA (ID: 2021.2.00008.S), which has about two times higher angular resolution (corresponding to < 1 pc) and sensitivity. As a result, we identified twice as many clouds associated with N132D. We further made a ^{12}CO(3-2)/^{12}CO(1-0) ratio map at pc-scale and found that the ratio is higher in the X-ray shell interior and lower in the shell exterior. This trend is consistent with Sano et al. (2020), suggesting that the clouds in the shell's interior correspond to post-shock regions. Based on the spatial distribution, temperature, and density of the interstellar clouds, we plan to extract spectra for each small spatial region and evaluate the mechanisms of thermal and non-thermal X-ray emissions.

Modeling the mixed-morphology supernova remnant VRO 42.05.01

Poster

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Abstract

VRO 42.05.01 is an evolved Galactic supernova remnant (SNR) that has been classified as a mixed-morphology SNR, showing a shell-like morphology in the radio band and centrally dominated X-ray emission. The remnant reveals a very intriguing morphology consisting of two major components, a 30' semi-circular shell and a larger triangular component. This peculiar morphology indicates that the remnant probably encountered a non-homogeneous ambient medium during its evolution. In this work, we aim to investigate the origin of the complex morphology and X-ray emission observed in VRO 42.05.01, and determine the geometry and density distribution of the ambient medium. To this end, we developed a 3D hydrodynamic (HD) model for VRO 42.05.01, which describes the interaction of the SNR with the non-uniform environment, characterized by a low density cavity and interstellar clouds. We performed an ample exploration of the parameter space describing the initial blast wave and the environment, including the mass of the ejecta, the energy, and the position of the explosion, as well as the density, structure, and geometry of the surrounding ambient medium. From the simulations, we synthesized the X-ray emission maps and compared them with actual X-ray data collected by XMM-Newton. Here we present the results of our exploration that allowed us to constrain the main parameters characterizing the remnant, including the density structure of the pre-SN environment, and shed light on the origin of the centrally-peaked X-ray emission of the remnant.

Session 3.

SN/SNR Progenitors, Central Engines, Explosion Models – Oral Talks

What will Eta Car look like in two thousand years?

Oral Talk

John Raymond, Nelson Caldwell

Center for Astrophysics, USA

Abstract

High resolution spectra of many nebulae in M31 were obtained with the fiber-fed Hectochelle spectrograph on the MMT. One object stood out as having very broad emission lines (-2000 to $+2000$ km s^{-1}) and an [N II]/Hα intensity ratio of 5-10. The [N II] emission is so dominant that the [S II]/([N II]+Hα) ratio is small, and the objects was not considered to be a supernova remnant. The line profiles of [O II], [N II] and [S II] all show peaks at about -750, -50 and $+800$ km s^{-1} in the M31 frame. The strong overabundance of N and the apparently bilobal morphology indicated by the line profiles are reminiscent of Eta Car. We speculate that if Eta Car explodes in about 1000 years, its remnant will resemble the M31 SNR when it reaches an age of about 1000 years.

Typing thermonuclear explosions from observations of young supernova remnants

Oral Talk

Gilles Ferrand[1], Samar Safi-Harb[1], Shigehiro Nagataki[2], Masaomi Ono[3], Donald Warren[4], Friedrich K. Röpke[5], Ivo R. Seitenzahl[6], Ataru Tanikawa[7], Anne Decourchelle[8]

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Abstract

Type Ia supernovae (SNe) are believed to mark the thermonuclear explosion of a white dwarf (WD). Despite their importance in cosmology, their progenitor system and explosion mechanism are still unclear. Igniting a WD requires some interaction, a major question being whether one WD (single degenerate) or two WDs (double degenerate) are involved. Another theoretical interrogation is whether the exploding WD is close to the Chandrasekhar mass limit, or well below it. Young supernova remnants (SNRs) can be used as a probe of the explosion physics. In particular a variety of diagnostics are available from X-ray observations of the shocked plasma. Recent progress in the simulation of SNe has shown the importance of turbulence and asymmetries in successful explosions, which prompts us to revisit the subsequent phase, the SNR phase. Can we use the SNR morphology as a probe of the explosion mechanism? Our SN2SNR project targets the thermonuclear case and makes the connection between the explosion physics and the remnant dynamics. We have run 3D simulations of a SNR starting from the output of state-of-the-art 3D SN simulations. We started with the N100 model, the canonical case of an accreting Chandrasekhar-mass WD that is undergoing a delayed detonation. By analyzing the wavefronts we quantified the imprint of the explosion on the remnant over time. Assuming a uniform ambient medium, we found that the impact of the SN on the SNR may still be visible after hundreds of years. We then performed a first comparative study of variants of this explosion model, in terms of the ignition pattern (N5 vs N100) and the propagation of the flame (deflagration vs detonation), which bear different levels of asymmetry. Lastly we investigated a different kind of model, where a sub-Chandrasekhar mass primary WD explodes via a double detonation while the secondary WD survives and is ejected away. This scenario has been called a “dynamically-driven double-degenerate double-detonation” or D^6. Our simulations again reveal specific signatures of the progenitor system and explosion mechanism, in particular a large and long-lasting conical shadow in the ejecta. Our ongoing work shows the intrinsic diversity of thermonuclear SNe and their remnants, and offers new perspectives for the interpretation of observations of young SNRs.

Supernova remnants as probes of the core-collapse supernova engine and its progenitors

Invited Talk

Chris Fryer

Los Alamos National Laboratory, USA

Abstract

NuSTAR observations of the Cassiopeia A supernova remnant proved the potential supernova remnants have in probing the nature of the core-collapse supernova engine. Supernova remnants have the potential to not only probe the engine, but the nature of the massive star progenitors as well. However, a number of pitfalls in the comparison between observations and a fundamental understanding of core-collapse supernova limit what we have learned thus far from these observations. Here we review study the current state-of-the-art of core-collapse supernova remnant studies, focusing on the tools needed to bridge these pitfalls. The combined studies produce a pipeline that can help the study of supernova remnants to reach their potential as probes of the core-collapse supernova engine and its progenitors.

Using JWST to observe supernovae from days to years past explosion

Oral Talk

Chris Ashall

Virginia Tech, USA

Abstract

The recent Launch of the James Webb Space Telescope has transformed our understanding of supernovae (SNe) explosions. In this talk I will present some of the most exciting JWST-SNe results from the MidInfared SuperNovA Collaboration (MIRSNAC). To date, MIRSNAC has been awarded over 180 hours of JWST time through 10 successful proposals spread over the first 5 cycles. I will present some of the first-ever JWST observations of type Ia SNe (SNe Ia) and core-collapse SNe (CC SNe). For CC SN, I will show observations of the SNe II: 2022acko and 2023ixf. Where I will demonstrate how JWST data can be used as a pathway to understand the formation, composition, and evolution of molecules and dust produced in the ejecta. For SNe Ia, I will present JWST observations of SN 2021aefx and SN 2022xkq, where I will show how JWST data can be used to accurately measure the mass of the primary white dwarf, as well as chemical asphericities within the explosion. Finally, I will project forward and discuss what future scheduled JWST-SNe observations will tell us.

New Insights into the Galactic Magnetar Population

Oral Talk

Ashley Chrimes

ESA/ESTEC, Netherlands

Abstract

The nature of the Galactic magnetar population is unclear. Are they a distinct population of neutron stars, or is there a continuum of initial rotational periods and magnetic field strengths? Are their extreme magnetic fields inherited from the progenitor (a "fossil" field), or are they generated in the neutron star formation process? And how are Galactic magnetars related, if at all, to the magnetars invoked as central engines in extragalactic transients? In this talk, I approach these problems from the viewpoint of binary stellar evolution. We explore whether any of the Galactic magnetars has a bound companion, by comparing their near-infrared counterparts with predictions from binary population synthesis. We then discuss the prospects for discovering more Galactic runaway (unbound) companion stars from supernova remnants and young neutron stars more generally. We find that with current surveys and facilities (from Gaia DR3 to JWST), the number of runaways can be increased by a factor of ~ 10. There is therefore great potential to obtain new constraints on the dynamics of supernovae in binaries, neutron star natal kicks, and when applied to magnetars, the promise of new insights into their progenitors.

Collimated Fe-rich ejecta in the magnetar-hosting supernova remnant Kes 73

Oral Talk

Marco Miceli[1], E. Greco[2], P. Zhou[3], S. Orlando[2], F. Bocchino[2], M.A. Aloy[4], M. Obergaulinger[4], N. Rea[5], J. Vink[6]

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Abstract

Magnetars are highly magnetized neutron stars with strong activity and high variability, manifested by powerful bursts in the X-ray and soft gamma-ray bands, often reaching the super-Eddington regime. Understanding their origin is crucial, considering that magnetars are invoked in several astrophysical environments: as central engines of gamma-ray bursts, in superluminous supernovae and in fast radio bursts. Two different scenarios have been proposed to explain the formation of these extreme objects: i) the dynamo model, with a rapidly rotating proto-neutron star powering an energetic SN explosion and ii) the fossil field scenario, involving a progenitor star with strong magnetic fields. Each of these mechanisms is expected to leave a specific imprint in the physical and chemical properties of the supernova remnant. Previous studies on the X-ray emission of supernova remnants hosting magnetars have shown indications of canonical explosion energies and relatively low masses for the progenitor stars, thus supporting the fossil field scenario. However, the X-ray emission of these remnants is typically dominated by the shocked interstellar medium, which hampers the diagnostics, because of the intrinsic difficulty in pinpointing the ejecta emission. We focus on the X-ray emission of the Galactic supernova remnant Kes 73, which hosts one of the most extreme magnetars observed, 1E 1841-045. Thanks to the combined analysis of XMM-Newton and Chandra observations, we reveal the X-ray emission component stemming from the ejecta. In particular, we report the discovery of an extended, elongated Fe-rich feature. The presence of such a collimated structure in the innermost ejecta is highly informative. In particular, we discuss our results in the framework of magnetorotational supernovae and discuss possible implications on the magnetar formation.

Massive star progenitors of SNe and SN remnants with strong CSM interaction

Invited Talk

Nathan Smith

University of Arizona, USA

Abstract

I will discuss both observational and theoretical aspects of massive star evolution involving strong mass loss in the late phases before death, leading to very strong CSM interaction in supernovae and their evolving remnants. Signatures of strong CSM interaction are observed in a variety of SNe, usually classified as Type IIn and Ibn, but also oddballs that are sometimes hard to classify. The observationally inferred pre-SN mass loss ranges from very strong stellar winds up to truly absurd cases where 20 $M_{\odot}$ is ejected in the decade before death. Proposed mechanisms include degenerate flashes, wave driving, massive star instabilities like LBV eruptions (not really a mechanism, but an observed phenomenon), the pulsational pair instability, and violent binary interaction or mergers, including mergers with compact objects. These make different predictions for the amount of mass lost, the ejection speed, and the duration of enhanced mass loss, which translate to different amounts of mass with different geometry and at various radii from the progenitor at the moment of death. Comparing these expectations to observed signatures of CSM favors certain mechanisms and rules out others.

3D Long-Term Evolution of CCSN: Connecting Explosive Dynamics to Electromagnetic Observations

Oral Talk

Michael Gabler

University of Valencia, Spain

Abstract

We investigate the intricate dynamics of core-collapse simulations, focusing on their three-dimensional, long-term evolution after shock revival until about 1y of the early SNR stage. Our numerical simulations are based on a simplified (gray, ray-by-ray) treatment of the neutrino heating during the explosion, but capture all relevant hydrodynamic instabilities consistently. The evolution is characterized by four different phases: i) Rayleigh-Taylor instabilities that enhance the mixing of elements within expansion of the ejecta. ii) Interaction between evolving structures and (reverse) shocks, during the propagation of the ejecta within the progenitor star. iii) Radioactive beta-decay causing inflation of Ni-rich structure and the connected influence on the evolving system's morphology. iv) Radiative cooling of metal-rich ejecta through a simplified treatment, treating it as an energy sink term within the model. Additionally, we discuss how we can use quantitative approaches to describe the resulting morphologies of the ejecta. We have used different techniques such as spherical harmonics or the statistics of the clumps. In this talk, we will highlight the use of a tool that is applied for the first time in the context of the analysis of 3D morphology: genus statistics. Furthermore, we emphasize the importance of connecting theoretical simulations to electromagnetic observations. Our models can be the basis for further modeling of light-curves, spectra or molecule/dust formation. By bridging simulation results with observational data, we aim to uncover observable signatures of core-collapse events and enhance our understanding of these phenomena. In summary, we discuss the results of long-term CCSN simulations in three dimensions, from shock revival to early supernova remnant stages. In order to improve on quantitative comparison of the obtained elemental morphologies to observations, we show a new tool in 3D: genus statistics.

The population of binary companions next to stripped-envelope core-collapse supernovae

Oral Talk

Manos Zapartas[1], Ori Fox[2], Schuyler van Dyk[3], Maria Drout[4], Azalee Bostroem[5], Ben Williams[6], Mathieu Renzo[7], Dimitris Souropanis[1], Tassos Fragos[8]

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Abstract

Stripped-envelope supernovae (Type Ib, Ic, IIb, etc) comprise one of the main types of core-collapse events, marking the death of massive stars that lost their hydrogen-rich envelope before exploding. Although isolated, very massive stars are not excluded from being their progenitors, the majority of them are believed to get stripped during a mass transfer towards a stellar companion in a close binary system. Various deep searches in post-supernova images to identify a remaining stellar source in nearby supernova sites and in older supernova remnants have led to detections or strong constraints to the existence of a possible binary companion. I will present the observational sample so far of companions next to nearby stripped-envelope supernovae which provides valuable independent information about the supernova progenitor systems. This compilation of observed companions allows us to do the first statistical study of them as a whole, comparing it with the predicted population properties derived from binary population synthesis codes, either based on detailed binary models, such as POSYDON, as well as other parametric ones. We find that in most stripped-envelope supernovae a fairly unevolved companion star is expected next to the exploding star, contributing to the stripping of the latter and increasing its probability of exploding. The possible discrepancy of the narrow observed luminosity (and mass) distribution of the companions compared to the broader expected one may provide independent valuable information about uncertain phases of binary evolution of these progenitor systems.

Post-explosion hydrodynamics in 3D neutrino-driven supernova models

Oral Talk

Daniel Kresse

Max Planck Institute for Astrophysics, Germany

Abstract

Core-collapse supernovae (CCSNe) are among the brightest and most energetic events in the Universe. They mark the violent, explosive deaths of massive stars and give birth to neutron stars (NSs) and black holes (BHs), the most exotic compact objects known. After decades of intense research, the "neutrino-driven explosion mechanism"; has meanwhile been established as the most promising and widely accepted paradigm for ("standard" Type II) CCSNe. Nevertheless, the question remained whether the neutrino-driven mechanism can explain the characteristic properties of observed supernovae, such as explosion energies, nucleosynthesis yields, and NS and BH kicks and spins. In my talk, I will address this question by presenting most recent results from a large set of three-dimensional (3D) neutrino-hydrodynamics simulations of the Garching group that extend over timescales of many seconds, i.e., significantly beyond the times when the explosions are launched. I will show that the highly non-linear post-explosion dynamics of 3D CCSN models with coexisting in- and outflows enable the long-lasting growth of the explosion energy, the efficient production of radioactive isotopes such as ^{44}Ti and ^{56}Ni, and the development of large-scale ejecta asymmetries, with important implications for NS and BH natal kicks and spins. Our results demonstrate that state-of-the-art 3D models of neutrino-driven CCSNe — if evolved over sufficiently long timescales — can reproduce the typical explosion properties as deduced from astronomical observations.

Near-Infrared Spectroscopy of SNe Ia at Nebular Phases

Oral Talk

Sahana Kumar

University of Virginia, USA

Abstract

The rise of automated transient searches has increased the number of known Type Ia supernovae (SNe Ia) to the point where follow-up resources can only observe a small fraction of the total SN Ia population at nebular phases. Identifying key observables and their evolutionary timescales is necessary to strategically plan late time observations as SNe evolve into remnants. I use dozens of nebular phase NIR spectra to examine the distribution of material within the innermost region of the SN to test theoretical predictions for multiple origin scenarios. The detection and time evolution of the NIR [Ni II] 1.939 micron and [Fe II] 1.644 micron lines can be used to constrain the progenitor's mass and may yield additional clues regarding possible explosion mechanisms. I also search for NIR H and He emission lines to gauge the likelihood of SN Ia progenitors with non-degenerate companion stars. Finally, I will discuss the advantages and limitations of ground-based NIR spectroscopy and share observing strategies for different observing conditions.

Establishing a mass-loss rate relation for red supergiants

Oral Talk

Konstantinos Antoniadis[1,2], A. Z. Bonanos[1], S. de Wit[1,2], E. Zapartas[3], G. Munoz-Sanchez[1,2], G. Maravelias[1,3]

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Abstract

High mass-loss rates of red supergiants (RSGs) drastically affect their evolution, their final fate, and the type of the resulting core-collapse supernovae. Yet their mass-loss mechanism remains poorly understood. Various empirical prescriptions scaled with luminosity have been derived in the literature, yielding results with a dispersion of 2-3 orders of magnitude. We determine an accurate mass-loss rate relation using over 2000 RSG candidates, with UV to mid-IR photometry in up to 49 filters, in the Large Magellanic Cloud, and investigate the discrepancy reported in previous works. We determined the luminosity of each RSG by integrating the spectral energy distribution and the mass-loss rate using the radiative transfer code DUSTY. We established a mass-loss rate relation as a function of the luminosity and the effective temperature. Furthermore, we found a turning point in the mass-loss rate versus luminosity relation at approximately $\log(L/L_{\odot}) = 4.4$, indicating enhanced rates beyond this limit. Yang et al. (2023) found this limit at $\log(L/L_{\odot}) = 4.6$ in the Small Magellanic Cloud, hinting at a metallicity dependence. We show that this enhancement correlates with photometric variability. Additionally, we examined the effect of different assumptions on our models and found that radiatively driven winds result in higher mass-loss rates by 2-3 orders of magnitude compared to steady-state winds. Finally, we apply the same methodology to model a large sample of RSGs in the Small Magellanic Cloud, NGC 6822, and Milky Way, to find if metallicity affects mass loss.

Session 3.

SN/SNR Progenitors, Central Engines, Explosion Models – Posters

Exploring supernova gravitational waves with machine learning

Poster

Ernazar Abdikamalov, Ayan Mitra, Daniil Orel, Sultan Abylkairov and Bekdaulet Shukirgaliyev

Nazarbayev University, Kazakhstan

Abstract

Core-collapse supernovae are powerful explosions at the end of lives of massive stars. Neutron stars and mass black holes are born in these explosions. Despite decades of effort, the exact details of this process remain poorly understood. The strong gravitational waves (CWs) that are emitted in these explosions carry information about their sources, which, if detected, may allow us to learn more about these explosions. In this talk, I will review our current understanding of the GW emission in core-collapse supernovae. I will then focus on our work where we perform simulations of a large number of rotating models. We then apply machine learning techniques to explore if it is possible to extract the parameters of the source, including progenitor rotation and mass as well as the properties of high-density nuclear matter, from the bounce GW signal.

Estimation of progenitor of Kepler's SNR with precision X-ray spectroscopic analysis

Poster

Moe Anazawa[1], Hiroyuki Uchida[1], Takuto Narita[1], Satoru Katsuda[2], Keiichi Maeda[1], Kai Matsunaga[1] and Takeshi G. Tsuru[1]

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Abstract

Kepler's SNR (SN1604) is the latest historical Type Ia supernova (SNe) in our galaxy. While the explosion mechanism of Type Ia SNe is still controversial, it has been claimed that Kepler's SNR originates from the single-degenerate (SD) channel rather than the double-degenerate (DD), based on several pieces of observational evidence for forward shock interaction with the circumstellar material (CSM) (e.g., Katsuda et al. 2015; Kasuga et al. 2021). These previous observations suggest that the mass-loss rate and the velocity structure of the CSM agree with an asymptotic giant branch (AGB) star as a companion star of the progenitor. In this study, we accurately measure the abundance of the CSM with the Reflection Grating Spectrometer (RGS) onboard XMM-Newton, which enables us to constrain parameters such as mass, rotation velocity, and metallicity of the companion star for the first time. We find that the obtained abundance ratio of nitrogen to oxygen (N/O) ~ 2.6 is significantly higher than that of the surrounding environment, which is consistent with a $\sim$1.5 $M_\odot$ AGB star. Taking into account the lack of detection of AGB stars in the center region of Kepler's SNR (e.g., Schaefer & Pagnotta 2012; Bedin et al. 2014), we propose that this remnant can be explained by a core merger scenario, which results in no surviving companion star after the explosion. In this talk, we present these results and discuss the origin of Kepler's SNR.

Modeling binary systems that survive supernova explosions and give rise to gravitational waves

Poster

Jelena Petrovic[1], Bojan Arbutina[2], M. Jurkovic[1], A. Čeki[1], G. Djurašević[1]

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Abstract

The latest observations of gravitational waves by LIGO, Virgo and KAGRA scientific collaborations indicate that the observed gravitational wave emission originates in mergers of black holes with masses up to about 100 solar masses. The MOBY project (Modeling Binary Systems That End in Stellar Mergers and Give Rise to Gravitational Waves) aims at identifying and modeling the progenitors of such gravitational wave sources related to the most massive stellar-mass binary black hole systems that can potentially survive two supernova explosions. Within the project evolutionary models of rotating close (Case A) massive binary systems will be calculated with the MESA (Modules for Experiments in Stellar Astrophysics) numerical code. Here we give some preliminary estimates of the masses of pre-supernova stars. The final goal is to produce an extensive grid of detailed evolutionary models of rotating massive binary systems with the initial masses of couple of hundreds solar masses or more, in order to reproduce observed binary black hole systems and constrain the initial and final physical parameters of their progenitors.

*MOBY project is funded by the Science Fund of the Republic of Serbia within the PRIZMA call for the period 2024-2027.

Different, but still same: on the common(?) origin of the peculiar Type Iax SNe

Poster

Barnabas Barna

University of Szeged, Hungary

Abstract

Type Iax supernovae (SNe Iax) are possibly the most common subclass of thermonuclear SN explosions. However, due to observational limitations, less than a hundred SNe Iax have been discovered, and only 15 objects have been studied in detail to date. These peculiar explosions result in relatively faint objects, as their peak brightness varies between −13.5 and −18.5 magnitudes. The extreme diversity, which extends to other physical properties, raises the question of whether multiple progenitor channels are contributing to the subclass. The importance of the puzzle about their exact origin goes well beyond the classification. The Type Iax SN 2012Z is so far the only thermonuclear SN with an observed progenitor system, while multiple SN remnants (SN 1181, Sgr A East) have been associated with Iax-like explosions. In recent years, new spectral time series observations have been added to both extremities of the Iax luminosity range. Together with a few intermediate luminosity SNe, the slowly growing sample allows us to map the entire luminosity range of the group with various techniques, including spectral synthesis and abundance tomography. The direct comparisons of the derived physical and chemical properties indicate that the well-constrained parameters (including ejecta and radioactive Ni mass, expansion velocity, and spectral line evolution) show a continuous distribution in the subclass. Considering that the recent pure deflagration models show a good match with the observables and the intrinsic structure derived from abundance tomography, there is growing evidence that all SNe Iax share a similar origin. Moreover, the study of hypothetical relations between the physical properties, such as the correlation between the expansion velocity and the peak luminosity could provide a new indirect way of distance estimations.

The long-time evolution of accretion-induced collapse of white dwarfs to neutron stars

Poster

Eirini Batziou and Hans-Thomas Janka

Max Planck Institute for Astrophysics, Germany

Abstract

The accretion-induced collapse (AIC) of white dwarfs (WDs) is an alternative scenario to neutron star formation, apart from the massive stellar collapse, it can act as a site for heavy-element nucleosynthesis and is a candidate for fast-evolving transients. We present the results of the first long-time evolution of AICs spanning from the onset of the white dwarf collapse to the homologous expansion of the ejecta for a set of six models of non-rotating (1 model) and rotating (5 models) WDs with different initial masses, spin rates, and angular momentum profiles. Our simulations determine characteristic properties of AIC events, including ejecta masses, energy, geometry, neutron-to-proton ratio, entropy, and expansion time scale. Our findings indicate that AICs produce neutrino-driven outflows, exhibiting sub-energetic events with low explosion energies of approximately 0.1 Bethe. Neutron stars born in an AIC scenario have masses ranging between 1-1.4 solar masses and rotational periods of 1-5 ms. Our models yield outflows with total ejecta mass of 0.001 solar masses with a large spread in the neutron-to-proton ratio distribution and disfavor strong r-process nucleosynthesis. We find that AIC outflows show extreme asymmetries in their properties, in particular in the composition of the ejecta, which has a direct impact on the nucleosynthesis and on the electromagnetic signal of these transients. Our self-consistent dynamical simulations are an important step in advancing the physical understanding of AIC events, facilitating the investigation of their possible contributions to the heavy-element production in the universe and enabling predictions of their observational signatures of neutrinos, gravitational waves, and electromagnetic emission.

Massive progenitor parade of stripped-envelope supernovae

Poster

Zsofia Reka Bodola and Andrea P. Nagy

University of Szeged, Hungary

Abstract

A single star with significant mass-loss or a binary-system with heavy mass transfer are two possible progenitor channels for stripped-envelope supernovae (SESNe). However, distinguishing these two progenitor scenarios are under debate. In our work we investigate the possible traces of the progenitor evolution from simply the shape of the bolometric light curves of SESNe. For this, we create massive (from 15 to 60 $M_\odot$) single- and binary star models with the stellar evolution code MESA. After that we compare their inner structure, chemical composition and also analyse their synthesised bolometric light curves (LCs) generated by the SuperNova Explosion Code (SNEC). Both progenitor channel models naturally differ in their interiors and also their compactness. But, more interestingly the gained bolometric light curves are not only differ in their initial rise time, but they show diverse global LC features. Our binary models tend to produce broader peaks than their single-star counterparts. Moreover, regardless to the mass of the remaining surface He, only the binary channel are able to produce generally similar light variations as can be observed for some double-peaked type IIb SNe.

Evidence for episodic mass loss in red supergiants from the ASSESS project

Poster

Alceste Z. Bonanos[1], S. de Wit[1,2], F. Tramper[3,1], K. Antoniadis[1,2], E. Christodoulou[1,2], G. Maravelias[1,4], G. Munoz-Sanchez[1,2], E. Zapartas[4,1]

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Abstract

We present the results of the ERC-funded ASSESS project (2018-2024), which aims to determine whether episodic mass loss is a dominant process in the evolution of the most massive stars, by conducting the first extensive, multi-wavelength survey of evolved massive stars in the nearby Universe. ASSESS has produced the largest catalog of evolved massive stars (185 stars) and in particular of red supergiants (RSGs; 129 stars) in nearby galaxies at low Z beyond the Local Group. The brightest and reddest of these are candidates for episodic mass loss. We model the optical spectra of our red supergiants with MARCS models to measure stellar properties from their optical spectra, such as the effective temperature, extinction, and radial velocity. By fitting the spectral energy distribution, we obtained the stellar luminosity and radius for 97 RSGs, finding $\sim$50% with $\log(L/L_\odot) > 5$ and 6 RSGs with $R > 1400\ R_\odot$. We also find a correlation between the stellar luminosity and mid-IR excess of 33 dusty, variable sources. Three of these dusty RSGs have luminosities exceeding the revised Humphreys-Davidson limit and are expected to be progenitors of core-collapse supernovae. We speculate that 3 other hot, dusty RSGs (12% of the K-type sample) may have experienced a recent mass ejection and indicate them as candidate Levesque-Massey variables. The frequency of dusty RSG (26% of the sample), i.e. those that show evidence for recent episodic mass loss events, is expected to be related to the frequency of Type II supernovae with pre-existing CSM, such as the recent example of SN 2023ixf.

Considering the Single and Binary Origins of the Type IIP SN 2017eaw

Poster

Azalee Bostroem

University of Arizona, USA

Abstract

Although the majority of massive stars form in binary (or other multiple) systems, it is challenging to differentiate between single and binary progenitors of supernovae. One tool to look for binary progenitors is to combine constraints from multiple observables. Current population synthesis models show that binary evolution allows stars of lower mass (and therefore longer lifetimes) to explode. Thus, for hydrogen-rich supernovae, a progenitor that appears younger than its surrounding populations is a clear indication of prior binary evolution. SN 2017eaw is one of the closest Type IIP supernovae in the last decade with all near-explosion observations indicating a progenitor with a helium core mass of 4.4–6.0 $M_\odot$ (initial mass 13–15 $M_\odot$). However, analyses of the surrounding stellar population found little to no evidence of star formation, placing an upper limit of the helium core mass of 3.4 $M_\odot$ (initial mass 10.8 $M_\odot$), making SN 2017eaw a strong candidate for the definitive identification of a binary progenitor. I will present a reanalysis of the surrounding population, showing that with deeper observations and a more careful analysis, the population surrounding SN 2017eaw is actually consistent with the near explosion observations. Applying constraints from supernova light curve and late-time spectra modeling, red supergiant pre-explosion imaging, and population ages with rapid population synthesis modeling, I will show that the probability of the progenitor of SN 2017eaw being a single star is 65% and the probability of prior binary interaction is 35%. While we cannot say definitively whether SN 2017eaw came from a single or binary progenitor, I will show a framework which can be used to apply this technique to future observations.

Numerical models of magneto-rotational supernovae: dynamics, multi-messenger signals, and explosive nucleosynthesis

Poster

Matteo Bugli[1,2], Jérôme Guilet[2], Moritz Reichert[3], and Martin Obergaulinger[3]

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Abstract

The gravitational collapse of a massive star with a fast-rotating core sets the stage for the onset of magneto-rotational core-collapse supernovae (CCSN). The accreting central compact object (either a black hole or a proto-magnetar) is believed to be the central engine that can power up outstanding stellar explosions such as hypernovae and long gamma-ray bursts (GRBs). Current magnetohydrodynamic numerical models allow one to make quantitative predictions on the properties of the compact remnant, the multi-messenger signatures of the explosion, the launching conditions of the relativistic jet, and the explosive nucleosynthesis of new heavy elements contributing to the chemical evolution of galaxies. Such predictions depend crucially on the accuracy that simulations can ensure when computing quantities such as the spin-down of the central proto-neutron star, the magnetic transport of angular momentum, and the nuclear composition of the ejecta. I will present the results obtained by recent 3D magneto-rotational supernova models that aim at characterizing the multi-faceted dynamics of the outstanding stellar explosion. I will show how different magnetic field configurations during the gravitational collapse affect not only the explosion dynamics and the compact remnant properties, but also the associated multi-messenger emission. I will also present recent state-of-the-art explosive nucleosynthesis calculations based on the 3D CCSN models, demonstrating the profound impact of magnetic field topology in determining the efficiency of r-processes during the explosion, the production of heavy elements, and thus the chemical evolution of galaxies. In particular, I will show how only for aligned dipolar magnetic fields the supernova ejecta are sufficiently neutron-rich to produce elements beyond atomic number A$\sim$130. Moreover, the impact of the magnetic field's dynamics dominates over the uncertainties related to nuclear physics input used for the nucleosynthesis calculations, demonstrating the paramount importance of accurately modeling the dynamics of central engine.

3D MHD core-collapse supernovae code comparison: the impact of numerics on central engine's simulations

Poster

Matteo Bugli[1,2], Jérôme Guilet[2], Kei Kotake[3], Philipp Moesta[4], Bernhard Mueller[5], Martin Obergaulinger[6], Evan O'Connor[7], Tomoya Takiwaki[8], Vishnu Varma[9]

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Abstract

Magneto-rotational supernovae are outstanding cases of core-collapse supernovae (CCSN) where the combination of fast rotation and strong large-scale magnetic fields leads to extraordinarily powerful stellar explosions. The accreting central compact object (either a proto-magnetar or a black hole) can power up energetic transients such as hypernovae and long gamma-ray bursts, as the rotational energy of the stellar core is extracted by the action of magnetic fields and used to launch polar outflows that propagate through the stellar progenitor. A correct numerical modeling of these phenomena is critical to produce predictions on the properties of the compact remnant, the neutrino and gravitational wave signatures of the explosion, and the launching conditions of the relativistic jet that eventually could break out of the star and lead to the emission of the first electromagnetic transient. Such estimates can depend crucially on the simulation's accuracy in reproducing quantities such as the extraction of rotational energy from the central proto-neutron star, the winding of magnetic field lines promoting the launch of polar outflows, and the onset of non-axisymmetric instabilities that could hinder the outward propagation of the jet, However, it remains still unclear to what extent the findings of models of magneto-rotational explosions depend on the numerical details of the specific tool used to produce them (such as the adoption of Cartesian or spherical coordinates, full general relativity or modified Newtonian gravity, multi-dimensional neutrino transport or simplified leakage schemes). I will present results from a code-comparison project which considers, for the first time, the modeling of a prototypical 3D magneto-rotational explosion realized with various state-of-the-art CCSN numerical codes using different grid geometries, gravity treatment, and neutrino-matter interactions. All models consider the same stellar progenitor (s20) with a fast rotating core (1 rad/s) and a strong aligned dipolar magnetic field ($\simeq 10^{12}$ G), where we imposed the same well-defined non-axisymmetric initial perturbation to seed the kink instability in the outflow. I will show the impact that specific modeling choices have on the explosion dynamics, the properties of the central compact object, the stability of the polar outflow, and the multi-messenger emission associated to the magneto-rotational CCSN (both neutrinos and gravitational waves).

Obtaining accurate parameters of Type IIP progenitors in NGC 6822, IC 10 and WLM

Poster

Evangelia Christodoulou[1,2], S. de Wit[1,2], A. Z. Bonanos[1], G. Munoz-Sanchez[1,2], G. Maravelias[1,3], K. Antoniadis[1,2], D. Garcia-Alvarez[4] and M. Rubio Diez[5]

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Abstract

The supernova (SN) community infers progenitor properties from pre-explosion images, however the effective temperatures (Teff) of RSGs (progenitors of Type IIP SNe) are highly debated. The massive stars community, on the other hand, has been measuring Teff using the TiO bands present in the optical spectra usually available. However, the Teff measured from atomic lines in the J-band is more accurate, as TiO bands form at larger radii and lower temperatures. Improved Teff estimations lead to more robust estimations of mass loss, extremely valuable to both the massive stars and SN communities. The ASSESS project has conducted an optical survey in the nearby Universe (12 galaxies with Z $\sim$ 0.1 to 1.5 $Z_\odot$) searching for evolved massive stars, primarily detecting RSGs with infrared excess (i.e. circumstellar dust) which reveals mass loss. These evolved RSGs may produce events like SN2023ixf and SN2009ip, where evidence of circumstellar material (CSM) originating from episodic mass loss events that occurred earlier in the star's lifetime have been detected. In the northern hemisphere, this survey has produced the secure spectral classification of twelve RSGs in NGC 6822 and IC 10 (Z = 0.32 $Z_\odot$ and 0.45 $Z_\odot$). Follow up spectroscopy has been acquired in the J-band for seven of them using the EMIR detector at the Grand Telescope of the Canarias. Also, we observed one target from the literature (WLM 14), expanding our metallicity range to 0.14 $Z_\odot$, as we aim to study mass loss in the low metallicity regime. We present J-band temperatures for these sources and compare them to the TiO temperatures derived from optical spectroscopy.

Typing supernova remnant G352.7-0.1 using XMM-Newton X-ray observations

Poster

Lingxiao Dang[1], Ping Zhou[1], Lei Sun[1], Junjie Mao[2], Jacco Vink[3], Qian-Qian Zhang[1], and Vladimír Domček[3]

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Abstract

G352.7-0.1 is a mixed-morphology (MM) supernova remnant (SNR) with multiple radio arcs and has a disputed supernova origin. We conducted a spatially resolved spectroscopic study of the remnant with XMM-Newton X-ray data to investigate its explosion mechanism and explain its morphology. The global X-ray spectra of the SNR can be adequately reproduced using a metal-rich thermal plasma model with a temperature of $\sim$2 keV and ionization timescale of $\sim 3 \times 10^{10}$ cm^{-3} s. Through a comparison with various supernova nucleosynthesis models, we found that observed metal properties from Mg to Fe can be better described using core-collapse supernova models, while thermonuclear models fail to explain the observed high Mg/Si ratio. The best-fit supernova model suggests a ~ 13 $M_\odot$ progenitor star, consistent with previous estimates using the wind bubble size. We also discussed the possible mechanisms that may lead to SNR G352.7-0.1 being an MMSNR. By dividing the SNR into several regions, we found that the temperature and abundance do not significantly vary with regions, except for a decreased temperature and abundance in a region interacting with molecular clouds. The brightest X-ray emission of the SNR spatially matches with the inner radio structure, suggesting that the centrally filled X-ray morphology results from a projection effect.

Possible pre-supernova binary companion to the progenitor of the supernova remnant IC 443

Poster

Baha Dinçel[1], Günay Paylı[1], Ralph Neuhäuser[1], Aşkın Ankay[2] and Sinan Kaan Yerli [3]

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Abstract

We found an OB-runaway star HD 254577 as a probable pre-supernova (SN) binary companion to the progenitor of the supernova remnant (SNR) IC 443. HD 254577 is a hot and evolved star with an effective temperature of $T_{\rm eff} = 23000 \pm 1000$ K and a surface gravity of $\log(\mathrm{g}[\mathrm{cm/s}^2]) = 2.8 \pm 0.2$. It is most probably a single star with a peculiar velocity of $\mathrm{v}_{\rm pec} = 32.6^{+2.9}_{-2.2}$ km s^{-1}, lying at a distance of $d = 1700^{+53}_{-56}$ pc. The flight projection of the star back in time approaches a group of OB-type stars, possibly the parent cluster where the disrupted binary originated. Although the proper motion of the neutron star (NS) CXOU J61705.3+222127 was not measured precisely, its cometary tail implies it is moving away from the same origin. We determined the explosion center by tracing the proper motion of the OB-runaway star for 10, 20, and 30 kyr ages for the SN. The 2-D space velocity of the NS at a distance of $d = 1.7$ kpc for these positions and the flight times are 159, 254, 537 km s^{-1}, which are consistent with the space velocity distribution of pulsars. By identifying the pre-supernova companion and the possible parent cluster, we show that the progenitor mass can be as high as ~ 30 $M_\odot$, favoring the jet scenario previously proposed. As the OB-runaway star cannot move out of the SNR, the SNR distance is precisely determined as $d = 1700^{+53}_{-56}$ pc. We also discuss the expansion dynamics of the SNR due to the highly off-centered explosion site.

Black hole supernovae and their equation-of-state dependence

Poster

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Abstract

The theoretical outcomes of core-collapse supernovae are often assumed to be binary: either explosion is successful and a neutron star is left behind, or, shock revival fails and black hole (BH) formation ensues. Recent advancements in the field reveal a new scenario, where BH formation occurs within seconds of shock revival, while still culminating in a successful supernova. We continue to explore this novel BH formation channel that we call black hole supernovae. We perform axisymmetric simulations of a 60 $M_\odot$ star that leaves roughly half of its mass in the BH. We follow the evolution until days later, witnessing shock breakout of the star and the initial conditions for a bright transient. In this talk, I will demonstrate how uncertainties in the properties of nuclear matter at high temperatures affect the mass of the BH remnant, the final explosion energy, as well as the ejecta and its element composition.

Searching for surviving stellar companions of historical Galactic type Ia supernovae

Poster

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Abstract

Type Ia supernovae (SNe Ia) are the best known cosmological distance indicators at high redshifts. Their use led to the discovery of the currently accelerating expansion of the universe (Riess et al. 1998; Perlmutter et al. 1999), and are major tools in the exploration of the nature of dark energy (Rose et al. 2020; Hayden et al. 2021). These SNe are thought to occur when a white dwarf made of carbon and oxygen accretes sufficient mass to trigger a thermonuclear explosion. The explosion could occur via several channels: accretion from a companion star (single-degenerate (SD) channel) or via merging of two white dwarfs (double-degenerate (DD) channel). The core-degenerate (CD) model, where the WD merges with the electron-degenerate core of an asymptotic giant branch (AGB) star, may be also considered as DD channel. Both might contribute to the production of SNe Ia but their relative proportions remain a fundamental puzzle in astronomy. The increase in the empirical knowledge of SNe Ia has led to an enormous advance in their cosmological use, but we still need to completely understand the explosion mechanism. We have been trying to search for surviving companions of progenitors of historical Galactic SNe Ia with the aim of clarifying the origin of these cosmological candles (see e.g. Ruiz-Lapuente 2019). We identified candidate companion for Tycho Brahe's SN 1572 (Ruiz-Lapuente et al. 2019) whereas the SN 1006 remnant may have been the result of merging of two white dwarfs (González Hernández et al. 2012). The Johannes Kepler's SN 1604 suggest a CD scenario (Ruiz-Lapuente et al. 2018). We have recently investigated the SNR G272.2-3.2 where we have found a possible surviving M-type stellar companion (Ruiz-Lapuente et al. 2023). We will show here the details of the research we have done about these Galactic supernova remnants.

Electron-capture supernovae - Thermonuclear explosion or gravitational collapse? - The fate of sAGB stars on a knife's edge

Poster

Alexander Holas[1], Friedrich Röpke[1], Sam Jones[2], James Keegans[3], and Raphael Hirschi[4]

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Abstract

It has long been postulated that the onset of electron captures in degenerate high-density ONe cores of super-AGB stars would trigger a supernova, resulting in a collapse into a neutron star (NS). New models of these so-called electron-capture supernovae (ECSNe) suggest that while the full collapse to a NS is still a possibility, the energy release by the electron-capture reactions can also trigger a thermonuclear runaway initiating explosive thermonuclear burning and leaving behind a bound ONeFe remnant in a "thermonuclear ECSN"; (tECSN). So far, however, tECSNe remain purely in the realm of theory. No optical observables have been predicted from simulations that could be used for a direct comparison with astronomical observations of such transients, thus confirming or denying their existence. Initial studies suggest that tECSNe could reproduce the solar abundances of important and so far problematic isotopes such as ^{48}Ca, ^{50}Ti, ^{54}Cr, together with ^{58}Fe, ^{64}Ni, ^{82}Se, and ^{86}Kr as well as several Zn-Zr isotopes, without introducing new tensions with the solar abundance distribution. If tECSNe proved to exist in nature, even at a low occurrence rate, they would provide an elegant way to cover these remaining blemishes on the charts of astrophysical element production. Furthermore, the tECSN scenario could not only establish a new production sites for thus far problematic isotopes in the solar inventory, it could also have implications on NS formation rates or provide an additional way of probing nuclear reaction rates. In this work, we greatly expand on the existing tECSNe models, exploring a multitude initial conditions and ignition geometries, increasing the number of available models by an order of magnitude. With this, we are able to narrow down the precise conditions under which an ECSN can transition into a tECSN. Our initial results suggest that the critical central density below which the collapse can be halted by thermonuclear burning is somewhere between $\log \rho_c^{\rm ini} = 10.15$ and $\log \rho_c^{\rm ini} = 10.3$, with the precise value depending on the ignition geometry. Moreover, we update our existing nuclear post-processing network to utilize the latest nuclear reaction rates and weak rate tables. Here, we aim to provide a comprehensive set of nucleosynthesis yields for our tECSN models, as well as to investigate the dependency of our results on the used rates. Both our hydrodynamic simulations and nucleosynthesis calculations can then be used to make detailed predictions about the resulting remnant structure and composition. Finally, these results will be used as an input for our full 3D radiative transfer simulations, contributing the first-of-its-kind synthetic observables which will allow us to determine the feasibility of tECSNe as a realistic supernova scenario.

An unexplored regime of shock breakout: the effect of rapid thermalization on the observed spectrum

Poster

Christopher M. Irwin and Kenta Hotokezaka

University of Tokyo, Japan

Abstract

The first light that escapes from a supernova explosion in the shock breakout emission, which produces a bright flash of UV or X-ray emission. Standard theory predicts that the shock breakout spectrum will be a blackbody if the gas and radiation are in thermal equilibrium, and a Comptonized free-free spectrum if not. Using recent results which suggest that thermalization takes place faster than previously thought after the breakout, we show that another breakout scenario is possible in which the gas and radiation are initially out of equilibrium, but the time to reach equilibrium is shorter than the light-crossing time of the system. In this case, the observed spectrum differs significantly from the standard expectation, as light travel time effects smear the spectrum into a multi-temperature blend of blackbody and free-free components. We explore the necessary conditions to obtain this type of unusual spectrum, finding that it is relevant for some blue supergiant progenitors, and for fast shocks ($v \sim 0.1 \cdot c$) breaking out of an extended envelope or circumstellar medium. An application to the low-luminosity gamma-ray burst GRB 060218 is discussed.

Discovery of an extreme Red Supergiant in the LMC transitioning to a Blue Supergiant

Poster

Maria Kalitsounaki[1], G. Munoz-Sanchez[1,2], S. de Wit[1,2], A. Z. Bonanos[1], K. Antoniadis[1,2], K. Boutsia[3], E. Christodoulou[1,2], A. Udalski[4], E. Zapartas[5], G. Maravelias[1,5]

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Abstract

Red Supergiants (RSGs) are evolved massive stars that undergo significant mass loss through undetermined mechanisms. As these stars have been identified as progenitors of the most common class of supernovae (SNe), Type II-P, the study of the physical processes governing RSGs is crucial for comprehending this evolutionary state as well as their properties before the collapse. In this study, we present a very cool, luminous, extreme RSG in the LMC, which has recently undergone a dramatic transformation in its spectral appearance. The star has the highest mass loss rate among the RSGs in the LMC and is surrounded by dense circumstellar material. New and archival spectroscopy along with photometric data from over 30 years cover this change and reveal a magnificent evolution to a hotter stage. The star no longer displays RSG signatures as the spectrum after the transition is dominated by double-peaked emission lines and P Cygni profiles typically seen in sgB[e]. The change from late-M to sgB[e] helps to shed light on the fate of massive RSGs, the origin of sgB[e], and the lack of massive RSGs producing Type II-P SNe.

Improving supernova prescriptions in binary population synthesis using detailed stellar profiles

Poster

Eirini Kasdagli

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Abstract

The majority of massive stars are found in close binary systems where the interaction with their companion can sometimes alter their internal structure and lead to diverse and exotic core-collapse supernovae (CCSNe). In turn, SN fundamentally alter the characteristics of a binary due to their enormous mass loss and natal kicks that determine which binaries become gravitational wave sources. Thus, we want to inform binary evolution with motivated physics prescriptions of the convective engine behind the SN explosion. POSYDON, a binary population synthesis model, is ideal for implementing these models, as it can self-consistently evolve the structure of both stars along with their binary interactions very close to CC. I will present preliminary results of these SN models implemented in POSYDON, and provide statistics of CO mass distribution, ejecta masses and SN types that will result from a population synthesis analysis.

3D Simulation of SN Ia SNR: Effects of companion star and progenitor system

Poster

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Abstract

Type Ia supernovae (SNe Ia) serve as one of cosmic standard candles, but their exact progenitor channel is still an open question. In the single degenerate model (SD channel), one white dwarf accretes mass from its non-degenerate companion. Once its mass reach Chandrasekar mass limit, a SN Ia explosion is triggered. In the double degenerate model (DD channel), two white dwarfs merge and explode as SN Ia. These two channels may result in different SN ejecta, as in SD channel the ejecta is expected to impact the nearby companion star and forms asymmetrical structure. While in DD channel, the progenitor may explode as a single merged object, thus its SN ejecta should be more symmetric. As the SN ejecta evolves into supernovae remnants (SNR), the imprint formed by the companion interaction may affect the morphology of the SNR. Also the progenitor systems may have experienced different mass transfer histories and therefore forms different circumstellar material (CSM) environment, which may also affect the early SNR evolution. In this study, we first simulate the interaction between SN ejecta and the companion star in the SD channel. Then we use 3D hydrodynamics code RAMSES to simulate the interaction between the post-interaction ejecta with the surrounding materials, and follow the evolution into SNRs. In our simulation, we consider different ejecta models and different CSM structures, and we also track element distribution. We plan to find the difference of SNRs that originate from different SNe Ia progenitor channels, and compare our simulation with actual observations in order to constrain the progenitor channel of SNe Ia eventually.

Formation of Mg-rich SNRs by shell merger and its effect on the explodability

Poster

Kai Matsunaga[1], Hiroyuki Uchida[1], Takeshi Go Tsuru[1], Rei Enokiya[2], Toshiki Sato[3], Ryo Sawada[4], and Hideyuki Umeda[4]

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Abstract

Various elemental compositions in ejecta of supernova remnants (SNRs) are thought to reflect characteristics of their progenitors, but it is generally hard to constrain progenitor properties from observations of SNRs. Our recent analysis of a core-collapse SNR G359.0−0.9 reveals that this remnant is classified as Mg-rich type, attributed to a relatively high Mg-to-Ne ratio ($\sim$ 1.9 solar). While previous studies have found two other Mg-rich SNRs so far (N49B and G284.3−1.8; Park et al. 2003 and Williams et al. 2015), their origin is not fully understood yet. In order to comprehend the mechanism that increases Mg/Ne ratio, we applied a stellar evolution model published by Sukhbold et al. (2018) and systematically calculated Mg/Ne ratios with different progenitor masses. As a result, we found that the high Mg/Ne ratios of Mg-rich SNRs can be explained by a theoretically predicted shell merger process (Yadav et al. 2020), where burning shells are mixed and merged by violent convection in the final phase of a massive star. Once it occurs, Ne is transported to the inner layer and the Ne-burning is enhanced, which results in Mg-rich ejecta. In our calculation, we also found that there are two separated Mg-rich groups attributed to the shell merger process: 14–24 $M_\odot$ stars with high Si/Mg ratios (>1 solar) and $< 15\ M_\odot$ stars with low Si/Mg ratios (≤ 1 solar). Considering the Si/Mg ratio of G359.0−0.9 ($\sim$ 1.3 solar), we conclude that the initial mass of the progenitor of G359.0−0.9 is likely less than 15 $M_\odot$. More interestingly, we suggest that if a massive star more than 20 $M_\odot$ explode, the ejecta must be Mg-rich with a high Si/Mg ratio. The shell merger also affects the explodability since the mixing process reduces the mass accretion rate onto the surface of a stalled shock, hence massive stars of more than 20 $M_\odot$ can explode only via the shell merger process. Therefore, we expect that Mg-rich SNRs are promising candidates for remnants of such massive progenitors more than 20 $M_\odot$, evidence for which has been elusive so far (cf. Smartt et al. 2009). In this presentation, we present our result of G359.0−0.9 and our findings on the shell mergers.

[W60] B90: a mass-losing luminous RSG in the LMC interacting with the CSM

Poster

Gonzalo Munoz-Sanchez[1,2], S. de Wit[1,2], A.Z. Bonanos[1], P. Boumis[1], K. Boutsia[3], A. Udalski[4]

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Abstract

Red Supergiants (RSGs) are evolved massive stars with initial masses between 8-25 $M_\odot$, which are assumed to be progenitors of Type II Supernova (SN). However, the lack of observations of Type II SNe produced by RSGs with an initial mass greater than 18 $M_\odot$ creates a conflict. The well-known "RSG problem" suggests that massive RSGs either collapse directly into a black hole without an explosion or evolve to warmer stages, where they end their lives in a post-RSG phase. Yellow supergiants with circumstellar dust have already been proposed as post-RSG candidates. Nevertheless, the physical process that induces an RSG to become a warmer supergiant is currently unclear. According to current evolutionary models, the RSG winds are not strong enough to make them evolve to a warmer stage. Moreover, other processes might be needed to strip their envelopes, such as episodic mass-loss or binary interactions. In this talk, we present an in-depth study of [W60] B90, one of the largest, most massive, and luminous RSG in the Large Magellanic Cloud (LMC) that shows evidence of current mass loss and interaction with their circumstellar material (CSM). Although it is a progenitor candidate for Type II SNe, its high mass places it in the "RSGs problem" range. Therefore [W60] B90 presents the perfect laboratory to study evolved massive RSGs, how they interact with the CSM, and how they provide the material needed to explain the observables in some core-collapse SNe.

Progenitor constraint with CNO abundances of circumstellar material in supernova remnants

Poster

Takuto Narita[1], Hiroyuki Uchida[1], Takashi Yoshida[1], Kai Matsunaga[1], Moe Anazawa[1], Takeshi Go Tsuru[1], Jacco Vink[2], Satoru Katsuda[3], Takaaki Tanaka[4], Hideyuki Umeda[5] and Toshiki Sato[6]

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Abstract

Circumstellar material (CSM) produced by stellar winds blown out from stars reflects the progenitor history of supernova remnants (SNRs).The abundances of lighter elements of carbon (C), nitrogen (N), and oxygen (O) of CSM provide rich information for understanding progenitors and especially, the abundance ratios N to O (N/O) and N to C (N/C) of critically reflect the initial states of progenitors such as mass rotation velocities, metallicities, and convections. Some previous studies with the Reflection Grating Spectrometer (RGS) on board XMM-Newton have successfully measured the CNO abundances and the progenitor constraint with CNO abundances in CSM has become available. In this talk, we will introduce the new powerful method of progenitor constraint with CNO abundances in CSM for core-collapse (CC) SNRs and report the results of high-resolution spectroscopy of Galactic CC SNR RCW 103 (Narita et al. 2023) and G292.0+1.8 (Narita et al. submitted). We detected the N V ɪɪ line of these SNRs with RGS for the first time and found that RCW 103 has the high N/O (=3.8±0.1) and G292.0+1.8 has the low N/O (=0.3±0.1). By comparing our results with several stellar evolution models, we constrained the progenitor of RCW 103 (a single 10–12 $M_\odot$ progenitor with a medium rotation velocity $\lesssim 100$ km s^{-1}) and G292.0+1.8 (a progenitor in a binary system). The progenitor constraint method with CSM established by our studies is useful for future missions with microcalorimeters such as XRISM and Athena.

The binary progenitor for Type IIP supernovae

Poster

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Abstract

As the most common class (>50%) of core-collapse supernovae (SNe), Type II-P SNe have gained significant attention of astronomers. They exhibit a rich photometric and spectroscopic diversity, which is believed to arise from differences in the progenitor structure before explosion. Based on identifications for ∼20 progenitors of Type IIP SNe, it has been well established that red supergiant stars are the direct progenitors of Type IIP SNe. For a long time, only the single-star progenitor channel has been considered, and it has been poorly discussed whether they can arise from interacting binaries. It is only recently predicted in theory that interacting binaries may make a significant contribution to Type IIP SNe and partly account for the observed diversity. However, it still remains challenging to observationally distinguish the single and binary channels for a detected progenitor. In this poster, we report a comprehensive study on the progenitors and environments of a sample of Type IIP SNe. Our results provide observational evidence that interacting binaries are indeed a plausible progenitor channel. More investigations are still needed to further constrain the relative contributions from different progenitor channels.

Probing energetic infant pulsars with supernova emission lines

Poster

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Abstract

Many energetic supernovae (SNe) are thought to be powered by the rotational-energy of a highly-magnetized, rapidly-rotating neutron star. The emission from the associated luminous pulsar wind nebula (PWN) can photoionize the SN ejecta, leading to a nebular spectrum of the ejecta with signatures possibly revealing the PWN. SN 2012au is hypothesized to be one such SN. We investigate the impact of different ejecta and PWN parameters on the SN nebular spectrum, and test if any photoionization models are consistent with SN 2012au. We study how constraints from the nebular phase can be linked into modelling of the diffusion phase and the radio emission of the magnetar. We present a suite of late-time (1-6y) spectral simulations of SN ejecta powered by an inner PWN. Over a large grid of 1-zone models, we study the behaviour of the SN physical state and line emission as PWN luminosity, injection SED temperature, ejecta mass, and composition vary. We find that certain models can reproduce the oxygen lines luminosities of SN 2012au reasonably well at individual epochs, but we find no model that fits over the whole time evolution; this is likely due to the simple model setup. Using our derived constraints from the nebular phase, we predict that the magnetar powering SN 2012au had an initial rotation period $\sim 15\,\mathrm{ms}$, and should be a strong radio source ($F > 100\,\mu\mathrm{Jy}$) for decades.

Stellar mass black hole formation and multimessenger signals from core-collapse supernova simulations

Poster

Kuo-Chuan Pan

Institute of Astronomy, National Tsing Hua University, Taiwan

Abstract

Core-collapse supernovae (CCSNe) are among the most energetic events in the Universe and birthplaces of neutron stars and stellar-mass black holes in extreme conditions. In this talk, I will present the latest results of our multi-dimensional supernova simulations with self-consistent neutrino transport. In particular, I will discuss the explosion engine and how our simulations aid future searches of neutrino and gravitational wave emissions from core-collapse supernovae

Three years observations of the nearby type II SN2008bk

Poster

Giuliano Pignata

Universidad de Tarapacá, Chile

Abstract

In this poster I will present the results of a three years observational campaign on SN2008bk. This is a low luminosity type IIP SN exploded in the Sculptor Group galaxy NGC 7793 ($D = 3.4\,\mathrm{Mpc}$). On one hand pre-explosion optical and infrared munti-bands observations of the progenitor makes it one of the best constrained supernova progenitor stars. On the other hand, our multi-wavelength very dense temporal coverage makes this object an ideal laboratory to study the physical process shaping the light curve and spectra of a Type IIP SN at different epochs and link them with the progenitor and explosion mechanism.

The historic light curve of Eta Car's Great Eruption from its light echoes

Poster

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Abstract

The Great Eruption (GE) of Eta Carinae (Eta Car) in the mid-1800s was a spectacular astronomical event, visible to the naked eye (Smith & Frew 2011). It arose from a more than 100 solar mass evolved star in an eccentric binary system that suddenly ejected about 20 solar mass of material, today seen as the bipolar Homunculus nebula. The discovery of light echoes of Eta Car's GE (Rest et al. 2012) now offers us the opportunity to re-observe the entire event with modern instrumentation (e.g., Prieto et al. 2014, Smith et al. 2021a,b). With more than 10 years of monitoring the light echoes, we are now able to reconstruct the full 20+ year GE light curve to very high accuracy! While we can confirm the 3 peaks of the GE in the historic light curve, we find that the GE dramatically reddens during the 3rd peak. In addition, we are able to probe the photometric asymmetry of the same event, and we find that in one direction, the light curve derived from the light echoes is strikingly different from the other directions as well as the historic light curve. With this new information, we will be able to further constrain the physical mechanism that is behind the GE.

SN Ia supernova remnant with M dwarf companions

Poster

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Abstract

The surviving companion of the SN Ia that resulted in SNR G272.2-3.2. is very likely a M dwarf star. This is supported by its kinematical characteristics and its trajectory within the SNR. This opens the possibility of a single-degenerate scenario for an SN Ia with an M-type dwarf companion. We study the evolution with time of these surviving companions of SNe Ia.

"^{56}Ni problem" in Canonical Supernova Explosion

Poster

Ryo Sawada

The University of Tokyo, ICRR, Japan

Abstract

Core-collapse supernovae (CCSNe) remain a mystery due to an incomplete understanding of their explosion mechanisms. While recent state-of-the-art simulations have shown promising results in reproducing explosions, there is a discrepancy in the growth rates of explosion energy required to synthesize sufficient ^{56}Ni mass to match observations. The radioisotope ^{56}Ni plays a critical role in determining supernova brightness, yet its importance often eludes the explosion mechanism community due to challenges in directly estimating it from numerical data. This issue, referred to as the "^{56}Ni problem" has received attention in recent studies (Sawada et al. 2019; Suwa et al. 2019; Sawada & Suwa 2021). In this poster, I aim to elucidate the fundamental processes involved in the synthesis of ^{56}Ni in supernova explosions and the underlying mechanisms that drive these cataclysmic events. In addition, I will discuss the intricacies of the "^{56}Ni problem" with a focus on my own research results. Through this discussion, I intend to shed light on potential avenues for resolving this longstanding puzzle in CCSNe astrophysics.

The life story of stripped-envelope supernovae as told through JWST observations

Poster

Melissa Shahbandeh

Space Telescope Science Institute, USA

Abstract

Dust plays a crucial role in the evolution of the cosmos, yet its origins have long been enigmatic. This presentation focuses on the study of stripped-envelope supernovae (SESN) and the intricate physics involved in their dust production. Specifically, we delve into the observations made possible by the James Webb Space Telescope (JWST), which provide unprecedented insights into the formation of dust precursors such as CO and SiO in the aftermath of SESN explosions. By analyzing NIRSpec and MIRI spectroscopy data from nearby SESNs, we aim to unravel the poorly understood composition of SESN ejecta. I will present NIRSpec and MIRI early spectroscopy of a "once in a decade" nearby stripped-envelope supernova (SESN), SN 2023dbc, which, remarkably, has captured the emergence of dust precursors CO and SiO and allowed us to uniquely probe the poorly constrained ejecta composition of SESNe (DD-4436, DD-4520, GO-6213, PI: Shahbandeh). I will also present JWST observations of Type Ib SN 2024ahv (GO-4217, PI: Shahbandeh). Our findings challenge previous assumptions about dust production in SESNe, and provide critical insights into the physics governing dust production in these objects, advancing our understanding of their role in early cosmic dust enrichment.

Binary progenitor systems for Type Ic supernovae

Poster

Martín Solar and Michał Michałowski

Adam Mickiewicz University, Poland

Abstract

Core-collapse supernovae (SNe) mark the death of massive stars (> 8 Msun), being one of the most important mechanisms that produce heavy elements and halt the star formation in the interstellar medium, so they have a profound impact on galaxy evolution. Details of these processes depend on SN progenitors, however, it is unclear if Type Ic SNe (without hydrogen and helium lines in spectra) originate from the core-collapse of very massive stars or from less massive in binary systems. In order to constrain the respective progenitor lifetimes and initial masses, we study the molecular gas environments using high-resolution ALMA CO(2-1) observations, being the first statistically significant study of Type II and Ic SNe at scales comparable to giant molecular clouds. We show that Type II and Type Ic SNe are located in environments with similar molecular gas densities. This implies that their progenitors have comparable lifetimes, and therefore, equivalent initial masses. Our results support a binary interaction model for most Type Ic SN progenitors, due to mass exchange from a companion star, which explains the lack of hydrogen and helium lines in explosion spectra. This finding can be used to compute the SN metal production, and be implemented in sub-grid processes in order to improve the feedback and chemical mixing in numerical cosmological simulations.

Expansion measurements of Tycho's supernova remnant and their implications of the progenitor system

Poster

Takaaki Tanaka[1], Hiroyuki Uchida[2], Tomoaki Kasuga[3], Shiu-Hang Lee[1], Keiichi Maeda[1], Hiroya Yamaguchi[4],Brian J. Williams[5], and Aya Bamba[5]

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[2]Kyoto University, Japan
[3]University of Tokyo, Japan
[4]JAXA, Japan
[5]NASA, USA

Abstract

The nature of the progenitor systems of Type Ia supernovae have been one of the hot topics in the field of astronomy, and is still under considerable debate. This is true even for the case of Tycho's supernova whose explosion was witnessed in 1572 and whose remnant have been observed over and over again in a wide range of wavelengths. Our recent X-ray studies of Tycho's supernova remnants, one based on Chandra image analysis and another based on XMM-Newton spectroscopy, have provided important clues to solving this problem (Tanaka et al. 2021; Uchida et al. 2024). We analyzed Chandra data of Tycho's SNR taken in 2003, 2007, 2009, and 2015, and measured the velocity of the blast wave between each epoch. We discovered that the blast wave rapidly decelerated during the last ~ 15 yr. This finding can be explained if the blast wave recently hit a wall of dense gas such as a cavity wall. Spatially resolved spectroscopy with XMM-Newton was found to strongly support this finding. We divided the remnant into $15'' \times 15''$ square regions and extracted spectra from each of them. Three-dimensional velocity structure of the expanding ejecta was constrained based on the Doppler-broadened lines of intermediate-mass elements. The obtained velocity structure contradicts uniformly expanding ejecta, and is well explained if rapid deceleration occurs near the edge of the remnant. The cavity-like gas structure implied by our results would have been created by the activity of the progenitor system of Tycho's supernova. Such activity is naturally expected in a case where a single-degenerate system exploded.

Possible evidence of a jet-induced explosion found from X-ray and radio observations of a peculiar SNR G0.61+0.01

Poster

Hiroyuki Uchida[1], Yukiko Tanaka[1], Kai Matsunaga[1], Takuto Narita[1], Takeshi Tsuru[1], Keiichi Maeda[1], Shunya Takekawa[2], Tomoharu Oka[3], Takaaki Tanaka[4]

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[3]Keio University, Japan
[4]Konan University, Japan

Abstract

We report on the discovery of a jet-like bipolar motion of Fe-rich ejecta in a Galactic SNR G0.61+0.01. This remnant is located near the Sagittarius B Molecular Clouds and known to be a remnant of a core-collapse explosion (Koyama et al. 2007). Based on our XMM-Newton observations of G0.61+0.01, we revealed that G0.61+0.01 has an elongated east-west bipolar structure, whose length exceeds $\sim$ 15 pc. Both the eastern and western spectra indicate high-temperature ($\sim$ 2 keV) and extremely Fe-rich (6–7 solar) plasmas, implying that they are ejected from the core of a massive star. We also found a possible bipolar motion by measuring the line centroid of the Fe Kα line in each spectrum. We further discovered a clear anti-correlation between the plasma and a previously-reported high-velocity compact cloud (HVCC; Oka et al. 2022), suggesting an SNR-cloud interaction in G0.61+0.01. Our follow-up survey for some shock tracers such as SiO J=2-1 and HCN J=4-3 shows convincing evidence of gas motions with an opposite velocity direction toward the east and west. All the results support the idea that G0.61+0.01 is a remnant of a theoretically proposed jet-induced explosion (e.g., Maeda & Nomoto 2003; Tominaga et al. 2009). While similar scenarios have also been drawn for several SNRs (e.g., W49B; Lopez et al. 2013) based on their morphologies, our findings provide more direct evidence of the bipolar motion. Taking into account the lack of the detection of a compact object at the center, we speculate that G0.61+0.01 was formed by a jet explosion driven by a central black hole in a massive star. This scenario is also consistent with the fact that G0.61+0.01 is located in the central molecular zone (CMZ), where the star formation activity is relatively high. We therefore conclude that G0.61+0.01 is a remnant of a jet-induced explosion, possibly an energetic hypernova or a low-energy faint supernova (Nomoto et al. 2006).

Upper limits of ^{44}Ti decay emission in four nearby thermonuclear supernova remnants

Poster

Jianbin Weng[1], Ping Zhou[1], Hagai B. Perets[2], Daniel R. Wik[3], and Yang Chen[1]

[1]Nanjing University, China
[2]Technion-Israel Institute of Technology, Israel
[3]University of Utah, USA

Abstract

To identify progenitors and investigate evidence of He burning, we searched for decay radiation of freshly synthesized ^{44}Ti in four young nearby thermonuclear supernova remnants: Kepler, SN 1885, G1.9+0.3 and SN 1006, by analysing the up-to-date NuSTAR archival data. No apparent flux excess from the 68 and 78 keV line emissions accompanying decay was detected above the power law continuum applied for the remnants and the absorbed stray light. By comparing the inferred upper limits of the line flux and the initial ^{44}Ti masses with a wide variety of supernova nucleosynthesis models, we placed constraints on the supernova progenitors. We derived the first NuSTAR line flux upper limit for Kepler and ruled out most of the double-detonation scenarios with a thick He layer under low density. We estimated, for the first time, the upper limit for SN 1885, which is high because of the large distance yet still remains consistent with the He shell detonation. The new flux and mass limit of G1.9+0.3 derived from a longer total exposure is lower than the results from previous studies and evidently excludes explosive burning of He-rich matter. The relatively advanced age and the large spatial extent of SN 1006 have prevented meaningful constraints.

Session 4.

SNR Structure, Ejecta and Evolution – Oral Talks

XRISM Mission Status and Observations of the LMC SNR N132D

Oral Talk

Brian Williams[1], Hiroya Yamaguchi[2], Rob Petre[1], on behalf of the XRISM Collaboration

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[2]ISAS/JAXA, Japan

Abstract

On September 7th, 2023, the X-ray Imaging and Spectroscopy Mission (XRISM) lifted off from Tanegashima Space Center in Japan, ushering in a new era of high-energy astrophysics. XRISM, an international JAXA/NASA collaboration including participation from ESA, is an advanced X-ray observatory that will address some of the most important questions in astrophysics in the 2020s. XRISM will study all manner of astrophysical objects, including galaxies and clusters, AGN, X-ray binaries, supernova remnants, transient phenomena, stars, and the interstellar medium.

On January 5th, 2024, the "First Light" release from XRISM showed the resolved spectrum of N132D in the 1.7-8 keV band with an energy resolution of 5 eV, revealing sharp emission lines from Si, S, Ar, Ca, and Fe. N132D is a ~3,000 year old supernova remnant in the Large Magellanic Cloud. It is the most luminous SNR in the LMC at X-ray energies, and has been extensively studied in optical, IR, and X-ray energies, including a brief observation with the short-lived Hitomi mission in 2016. The Hitomi spectrum suggested, via the Fe K-alpha emission at 6.5 keV, that the Fe in the remnant, presumably resulting from the ejecta, is moving with a different bulk velocity from the S seen via an emission line at ~2.5 keV. These results have been confirmed with the XRISM spectrum, and the XRISM team is further analyzing these recently obtained data.

In this talk, I will present an overview of our results on N132D, including the likely detection of emission lines from charge exchange between heavy elements and neutral material in the surrounding medium. Additionally, I will give a general overview of the SNR science that XRISM will perform, as several remnants are being observed as part of the Performance Verification phase. We anticipate that many more will be observed as part of the General Observer phase, which will begin in the late summer of 2024.

Measuring ejecta mass ratios in Kepler's SNR to constrain its origin

Oral Talk

Tyler Holland-Ashford[1], Pat Slane[1], Laura Lopez[2], Katie Auchettl[3], Vinay Kashyap[1]

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[2] The Ohio State University, USA
[3] University of Melbourne, Australia

Abstract

Supernovae (SNe) drive galaxy evolution by chemically enriching and heating interstellar gas, but their rarity and distance can limit astronomers' ability to understand them. In particular, the exact origins of many Type Ia supernovae —even Galactic ones— remain uncertain. In this talk, I will present my work on analyzing the Suzaku X-Ray spectrum of Kepler's supernova remnant (SNR) in order to estimate the total mass ratios of various ejecta species synthesized during explosion. I then compare these results to the predictions of various Type Ia SNe simulations in order to place limits on the progenitor scenario and explosion processes that led to Kepler's SNR. In addition, I will discuss some of the challenges present in fitting complex, high-signal X-ray SNR spectra with multi-component atomic models and how these challenges can be overcome.

Deciphering Supernova Remnant Structure and Evolution

Invited Talk

Danny Milisavljevic

Purdue University, USA

Abstract

I will review efforts to understand the nature of supernovae and their progenitor systems through study of the structure and evolution of supernova remnants (SNRs). The growing need for comparisons between multi-wavelength, multi-epoch observations of SNRs and theoretical simulations in order to decipher the information encoded in the supernova's expanding debris and its interaction with surrounding mass loss environment will be highlighted. I will also describe preliminary results from a James Webb Space Telescope survey of the nearby (3.4 kpc), young ($\sim$350 yr), core-collapse SNR Cassiopeia A, that, for the first time, have made it possible to map the remnant's extensive web-like network of unshocked ejecta.

A JWST View of the Crab Nebula

Oral Talk

Tea Temim

Princeton University, USA

Abstract

The Crab Nebula (SN 1054 AD) is the first astronomical object identified as having resulted from a supernova explosion, and since its re-discovery almost 300 years ago it has been among the most studied objects in the sky. It has served as a benchmark for understanding neutron stars, pulsars, and supernova explosions, and yet, many basic questions about its origin still remain. I will present new JWST imaging and spectroscopic observations of the Crab Nebula that show this iconic supernova remnant in unprecedented detail. Some highlights include the first high-resolution map of dust distribution in the Crab's filaments, the detection of small-scale variations in synchrotron emission that provide the first direct evidence for curvature in the particle spectrum injected by the pulsar, and a measurement of elemental abundances in the ejecta that shed new light on the nature of the explosion that produced the Crab Nebula.

XRISM Observations of Cassiopeia A

Oral Talk

Paul Plucinsky, XRISM Cas A Target Team

Smithsonian Astrophysical Observatory, USA

Abstract

We present preliminary results from two X-ray Imaging and Spectroscopy Mission (XRISM) observations of the Galactic supernova remnant (SNR) Cassiopeia A (Cas A). Cas A is the youngest core-collapse SNR (t $\sim$ 350 yr) in the Galaxy and is known to be the remnant of a Type IIb progenitor from light echo spectra. Cas A has the highest flux in the 2-10 keV band among Galactic SNRs and is therefore a prime target for detailed X-ray spectroscopy. The XRISM Resolve instrument observed two regions in Cas A with its 3x3 arcminute field-of-view: one in the Fe-rich region in the SE for 182 ks and the other in the NW region for 167 ks. The Resolve high resolution spectra provide the most precise measurements to date of the redshifts and broadening of the bright emission lines of Si, S, Ar, Ca, and Fe in the X-ray bandpass. These high resolution spectra will be examined for evidence of emission from the odd-Z or trace elements, charge exchange, and radiative recombination features. The results of these analyses will be used to constrain the 3D velocity structure and the mass and metallicity of the progenitor.

Interpreting JWST observations of Cassiopeia A through 3D MHD modeling

Oral Talk

Salvatore Orlando[1], Hans-Thomas Janka[2], Annop Wongwathanarat[2], Dan Milisavljevic[3], Ilse De Looze[4], Daniel Patnaude[5], Marco Miceli[6], Fabrizio Bocchino[7]

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[2]MPA-Garching
[3]Purdue University
[4]Ghent University
[5]CfA
[6]Palermo University
[7]INAF-OAPa

Abstract

Recently, high-quality JWST observations of the galactic supernova (SN) remnant Cassiopeia A have provided new insight into its complex structure. Specifically, these observations have revealed the presence of an extended structure around the center of the remnant, visible in JWST/ MIRI emission F1130W and F1280, pockmarked by numerous nearly circular holes. The analysis of the observations has shown that this structure, dubbed the “Green Monster” due to its color in the images, consists of circumstellar material recently shocked. Furthermore, the observations have also uncovered an intricate web-like network of filaments of unshocked ejecta, likely indicative of phenomena occurring shortly after the onset of the SN explosion or as a result of local inflation caused by Ni bubbles. In this contribution, we investigate the origin of these new features discovered with JWST through high spatial resolution 3D (magneto)-hydrodynamic modeling. Our model describes the evolution of a neutrino-driven core-collapse SN from its onset to the age of Cassiopeia A. Additionally, the model accounts for the interaction of the remnant with an inhomogeneous circumstellar medium, characterized by the presence of an asymmetric dense shell, which probably resulted from an eruption of the progenitor star that occurred millennia before the SN event.

3D mapping of the ejecta of SN1987A with ALMA

Oral Talk

Roger Wesson

Cardiff University, United Kingdom

Abstract

Supernova 1987A is the nearest supernova explosion to Earth since the invention of the telescope, and as such, is the only core collapse supernova remnant that can be spatially resolved across the electromagnetic spectrum. The spatial distribution of molecules in its expanding ejecta provides constraints on hydrodynamical simulations of supernova explosions. Neutrino-driven supernova explosion models predict that instabilities in the early stages of the explosion cause the fragmentation of the ejecta into clumps, the distribution of which depends on numerous different model parameters. Mapping the 3D geometry of the expanding ejecta of a supernova thus provides observational constraints which explosion models should reproduce. We have obtained high spatial resolution observations with ALMA of CO and SiO within the ejecta, which we use to derive 3D maps and radial mass distributions of CO and SiO. We compare our results to the predictions of state-of-the-art hydrodynamical simulations.

SN 1987A in the JWST era — compact object, ejecta structure and CSM interaction

Invited Talk

Josefin Larsson

KTH Royal Institute of Technology, Sweden

Abstract

As the most nearby SN in the era of modern telescopes, SN 1987A has provided us with a unique observational record of the birth and early evolution of an SNR. This has given new insights into a wide range of topics covering everything from ejecta structure and composition to shock interaction and pre-SN mass loss. I will give an overview of the evolution of SN 1987A and particularly highlight recent discoveries with JWST. This includes the clear identification of emission associated with the compact object. The JWST observations show narrow lines from ionized argon and sulphur at the very center of the remnant, which shows that the compact object is ionizing the innermost ejecta. The ionizing radiation may be dominated by the thermal emission from the neutron star surface or the non-thermal emission from a pulsar wind nebula. Outside the innermost region, the freely expanding ejecta reveal the highly asymmetric nature of the explosion. The ejecta morphology has been reconstructed in 3D in several emission lines, which shows that different elements are well mixed and display a similar large-scale morphology resembling a broken dipole. Further out in the system, the fastest ejecta are interacting with the iconic ring-nebula, giving rise to bright multiwavelength emission. I will show how decades of monitoring with HST trace the propagation of the forward shock in the equatorial ring and the emergence of emission from the reverse shock. Recent observations from JWST and VLT have added to this by revealing the 3D morphology of the reverse shock for the first time, showing a bubble-like morphology. This sheds new light on the mass distribution between the rings and hence the evolution of the progenitor before the explosion.

Session 4.

SNR Structure, Ejecta and Evolution – Posters

X-ray diagnostics of Cassiopeia A's "Green Monster": evidence for dense shocked circumstellar plasma

Poster

Manan Agarwal, Jacco Vink

Anton Pannekoek Institute, University of Amsterdam, Netherlands

Abstract

The infrared images of the core-collapse supernova remnant, Cassiopeia A (Cas,A), using the MIRI instrument onboard the James Webb Space Telescope (JWST) revealed a large structure in the interior region, referred to as the "Green Monster". Although the central location suggests an ejecta association, the infrared properties of the Green Monster hint at a circumstellar medium (CSM) origin. We investigate the filamentary X-ray structures associated with the Green Monster using archival data from the Chandra X-ray Observatory. We extracted spectra along the Green Monster and from shocked CSM regions. The extracted spectra as well as a principal component analysis show that the Green Monster's emission properties are more similar to those of the shocked CSM than the ejecta. We employ the Bayesian scheme, BXA, to fit the extracted spectra with a model consisting of a combination of a non-equilibrium ionization model and a power-law component, modified by Galactic absorption. All the "Green Monster" associated spectra show a blueshift corresponding to a radial velocity of around -2300 km s^{-1}, suggesting that the structure is on the near side of Cas A. The ionization age is around $\sim 1.5\times\ 10^{11}$ cm^{-3} s, which implies a pre-shock density of ~ 12 cm^{-3}, higher than previous estimates of the unshocked CSM. The relatively high $n_{rme}t$ and relatively low radial velocity suggest that this structure has a relatively high density compared to other shocked CSM plasma. This provides yet another piece of evidence that the CSM around Cas A's progenitor was not that of a smooth steady wind profile.

Spectroscopic analysis tool for intEgraL fieLd unIt daTacubEs (SATELLITE): The case of SNR 0509-68.7

Poster

Stavros Akras[1], Panos Boumis[1], Lydia Konstantinou[1], Konstantinos Bouvis[1], Sophia Theodossiou[2], and Maria Kopsacheili[3]

[1]IAASARS, National Observatory of Athens, Greece
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[3]Institute of Space Sciences (ICE, CSIC), Barcelona, Spain

Abstract

The Spectroscopic analysis tool for intEgraL fieLd unIt daTacubEs (SATELLITE; Akras et al. 2022) is an automatic code written in Python that is designed to fully explore the capability of integral field unit (IFU) datacubes in the characterization of extended objects, such as planetary nebulae, H II regions, Herbig-Haro objects, galaxies, and supernova remnants. The PYNEB python package (Luridiana et al. 2015) is employed for the determination of the physico-chemical properties of the ionized nebulae such as the extinction, electron temperature, electron density, ionic and total chemical abundances. SATELLITE performs an 1D spectroscopic analysis for the direct comparison of the IFU observations with previous studies based on long-slit spectroscopy, and a 2D spectroscopic analysis for the investigation of physico-chemical properties in both spatial directions. We present the preliminary results from our spectroscopic analysis of SNR 0509-68.7 observed with MUSE@VLT using the SATELLITE code.

On the origin of the North Polar Spur

Poster

Dejan Urošević, Milica Andjelić and Arbutina Bojan

University of Belgrade, Faculty of Mathematics, Serbia

Abstract

Recently, Iwashita, Kataoka and Sofue (2023) reanalyzed the origin of the North Polar Spur (NPS) in order to determine whether it is very old local supernova remnant (SNR) or local superbubble created by a few subsequent supernova explosions from the same stellar association, or a distant object of immense extension, on the Galactic scale, associated with a giant explosion from the Galactic center. After comparative analysis, Iwashita et al. (2023) concluded that NPS is a rather distant object of Galactic dimensions than an old local old SNR or superbubble. Contrary to conclusion of Iwashita et al. (2023), by using the method presented in Urošević (2020, 2022), we show that the parameters obtained from radio observations are consistent with SNR (or superbubble) origin of NPS.

A Monte-Carlo Simulation on Resonant Scattering of X-ray Line Emission in Supernova Remnants

Poster

Yang Chen, Y. Li, G. Zhang, L. Sun, and S. Zhang

Nanjing University, China

Abstract

Resonant scattering (RS) of X-ray line emission in supernova remnants (SNRs) may modify the observed line profiles and fluxes and has potential impact on estimating the physical properties of the hot gas and hence on understanding the SNR physics, but has not been theoretically modeled ever. Here we present our Monte-Carlo simulation of RS effect on X-ray resonant-line emission, typified by OVII Heα r line, from SNR. We employ the physical conditions characterized by the Sedov-Taylor solution and some basic parameters similar to those in Cygnus Loop. We show that the impact of RS effect is most significant near the edge of the remnant. The line profiles are predicted to be asymmetric because of different temperatures and photon production efficiencies of the expanding gas at different radii. We also predict the surface brightness of the line emission would decrease in the outer projected region but is slightly enhanced in the inner. The G-ratio of the OVII Heα triplet can be effectively elevated by RS in the outer region. We show that RS effect of the OVII Heα r line in the southwestern boundary region of Cygnus Loop is non-negligible. The observed OVII G-ratio ~ 1.8 of the region could be achieved with RS taken into account for properly elevated O abundance from the previous estimates.

Thermal X-ray Emission in the Western Half of the LMC Superbubble 30 Dor C

Poster

Yi-Heng Chi[1], Han-Xiao Chen[1], Yang Chen[1], Yi-Fan Meng[1], Ping Zhou[1], Lei Sun[1] and Wei Sun[2]

[1]Nanjing University, China
[2]PMO

Abstract

While 30 Dor C is a unique superbubble in the Large Magellanic Cloud for its luminous non-thermal X-ray emission, the thermal X-ray emission it emanates has not yet been thoroughly investigated and well constrained. Based on the separate ~ 1 Ms deep XMM-Newton and Chandra observations, we report the discovery of the thermally-emitting plasma in some portions of the western half of 30 Dor C. The thermal emission can be reproduced by a collisional-ionization-equilibrium plasma model with an average electron temperature of ~ 0.4 keV. We find a significant overabundance of the intermediate-mass elements such as O, Ne, Mg, and Si, which may be indicative of a recent supernova explosion in 30 Dor C. Dynamical properties in combination with the information of the OB association LH 90 suggest that the internal post-main-sequence stars dominate the power of the superbubble and blow it out in the past ~ 1 Myr.

Observational study of the reversed shocked ejecta in SNR 0509-67.5

Poster

Priyam Das and I. Seitenzahl

UNSW Canberra, Australia

Abstract

Type Ia supernovae, which mark the catastrophic demise of compact white dwarfs in close binary systems, serve as crucial probes for understanding dark energy and are believed to be significant sources of positrons, or anti-matter, within our Galaxy. Despite their pivotal role across various astrophysical domains, the debate persists regarding their explosion mechanisms. Are they the result of a near-Chandrasekhar mass white dwarf exploding due to mass transfer from a companion, or do they originate from less massive white dwarfs, potentially through mergers or triggered by helium shell detonations? This enduring question forms the crux of the ongoing debate surrounding the progenitors and explosion mechanisms of thermonuclear supernovae. In my talk, I will show how an increasing number of extraordinary shock-excited optical emission lines observed in the ejecta of young Type Ia supernova remnants can provide novel constraints on the explosion mechanisms of Type Ia supernovae.

High resolution mapping of the unshocked ejecta in Cassiopeia A

Poster

Danielle Dickinson[1], Danny Milisavljevic[1], Martin Laming[2], John Raymond[3], Tea Temim[4], Bon-Chul Koo[5], Richard Arendt[6], Rob Fesen[7], and Grace Katz[1]

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Abstract

We present near- and mid-infrared, high resolution, JWST observations of unshocked ejecta in the supernova remnant (SNR), Cassiopeia A (Cas A). These observations map previously unseen inner debris in great detail that closely traces the dynamics of the original core-collapse supernova from a stripped-envelope massive progenitor star. This enables a unique opportunity to investigate the explosion mechanism behind the youngest, Galactic core-collapse SNR. We investigate multiband imaging of Cas A and four Integral Field Unit spectral cubes, taken as part of a survey of the SNR, with special attention to the 3D distribution of various elements of the unshocked ejecta. We reconstruct, with unprecedented spatial (∼0.2") and spectral resolution (R∼1, 630 – 3,710), the distribution of [S III], [S IV], [O IV], [Ne II], and [Ar II] from two centrally located IFUs. We observe clumpy, unshocked ejecta filaments, consistent with turbulent mixing of the progenitor's oxygen layer with neutrino and radioactively heated matter. We investigate strategies for follow-up observations involving additional IFU positions to sample the chemical abundances and distribution across all of Cas A's inner ejecta.

Theoretical and experimental simulations of colliding blast waves

Poster

Marin Fontaine, C. Busschaert, and E. Falize

CEA, DAM, DIF, Arpajon, France

Abstract

After its explosion, the supernova remnant (SNR) goes through different phases, dispersing its energy into the interstellar medium (Truelove & McKee 1999). After about a thousand year of evolution, the SNR is decelerating in its Sedov phase. It is during this phase that the SNR may collide with other objects, such as molecular clouds or other SNRs. The development of laboratory astrophysics using high energy-density laser experiments has made it possible to reproduce and study many different astrophysical phenomena (Remington et al. 2006), such as a SNR in the Sedov phase. The collision of such blast waves with other objects in the laboratory was performed at the LULI2000 laser facility (Albertazzi et al. 2020). In this work, we reproduced this experiment numerically using the radiative hydrodynamics Arbitrary Lagrangian Eulerian code TROLL (CEA-DAM), in order to study the expansion of these blast waves and their collisions in greater details. This will then enable to reproduce numerically the compression of a dense molecular cloud by a SNR in the laboratory.

Hydrodynamic instabilities in three-dimensional simulations of neutrino-driven supernovae of 14 red supergiant progenitors

Poster

Beatrice Giudici[1], M. Gabler[1], and H.-T. Janka[2]

[1]Universitat de Valencia, Spain
[2] Max-Planck-Institute for Astrophysics, Germany

Abstract

We investigate core-collapse supernova (CCSN) explosion simulations of 14 different red supergiant (RSG) progenitors. The RSG stars were evolved as single-star progenitors in 1D and have zero-age main-sequence (ZAMS) masses between 12.5 and 27.3 solar masses. The explosions were modelled with the neutrino-hydrodynamics code Prometheus-HotB. The simulations were carried out in full-3D geometry and were evolved from the onset of core collapse until 10 days after the explosion. The obtained explosion properties, such as explosion energies or nickel yields, and the properties of the neutron star (NS) are in agreement with theoretical expectations, previous works, and observations. The main question we are interested in is the mixing of elements in 3D and how it can be related to the properties of the progenitor star. In particular, we investigate the growth of Rayleigh-Taylor instabilities (RTIs) at (C+O)/He and He/H interfaces. These instabilities have an important role in the outward mixing of ^{56}Ni into the hydrogen envelope. Moreover, we analyze the velocity of the ^{56}Ni yields at different times throughout the explosions and relate them to the respective progenitor structure. We claim that the initial stellar profile of the function ρr^3 plays an important role in the propagation of the shock (Sedov 1959), and in particular its shape in the He shell has been proven to play a fundamental role in the characterization of SN explosions.

Measuring the initial mass of ^{44}Ti in SN 1987A through the ^{44}Sc emission line

Poster

Roberta Giuffrida, M. Miceli, V. Sapienza, E. Greco, S. Orlando, and F. Bocchino

Universitá degli studi di Palermo, INAF - OAPa, Italy

Abstract

Radioactive isotopes in supernova remnants encode important information about the processes at work shortly after the collapse of the progenitor star. Their detection, the analysis of their distribution, and the estimation of their mass are therefore of paramount importance in constraining current models of supernova explosions. One notable example is ^{44}Ti, which can be effectively studied through its hard X-ray emission lines, providing a powerful diagnostic tool for probing the explosive nucleosynthesis processes within the inner layers of the exploding star. In this framework, SN 1987A serves as a privileged laboratory due to its proximity, youthful age, and the wealth of dedicated X-ray observations. However, some tension exists in the measure of the initial mass of ^{44}Ti in SN 1987A (M_{44}), since previous studies, based on the analysis of *NuSTAR* and *INTEGRAL* data, report $M_{44} = (1.5 \pm 0.3) \times 10^{-4}\ M_\odot$ and $M_{44} = (3.1 \pm 0.8) \times 10^{-4}$ M$_\odot$, respectively. In this project, we measure the initial mass of ^{44}Ti in SN 1987A through the ^{44}Sc emission line at 4.09 keV using multi-epoch *Chandra* archive observations, focusing our spectral analysis on the inner regions of the remnant to minimize contamination from X-ray emission originating from shocked plasma (both circumstellar material and outer ejecta). We find significant line emission in the 2000-2004 epoch, where there is the lowest contamination from thermal emission, and 2016-2021, where the emission line is less absorbed by the cold ejecta. We also derive tight upper limits on the line flux in the 2005-2009 and 2010-2015 epochs, thus reconstructing the temporal evolution of the line flux. We estimate the (time-dependant) absorption of the emission line associated with cold ejecta, to derive the initial mass of ^{44}Ti. We then find $M_{44} = (1.2 \pm 0.4) \times 10^{-4}$ M$_\odot$. This value is in agreement with that obtained from *NuSTAR* observations.

Mapping the 3D dynamics and spectral properties of Tycho's SNR in X-rays

Poster

Leïla Godinaud, F. Acero, A. Decourchelle, and J. Ballet

CEA Saclay-AIM, France

Abstract

The Tycho SNR is the 450-year-old remnant of the historical Type Ia supernova SN 1572. The study of these young Galactic remnants offers a unique opportunity to measure the ejecta dynamics and nucleosynthesis as a probe of Type Ia explosion mechanisms. To investigate the properties of the progenitor system, we have obtained a detailed view of the three-dimensional ejecta dynamics using the deep archival Chandra X-ray observations. This resulted in a field of 1500 velocity vectors in the plane of view (Vxy), along with an integrated velocity map in the line of sight (Vz), providing total coverage of the remnant at the 2" level. This revealed small- and large-scale velocity asymmetries. These anomalies in dynamics could stem from inherent factors, such as anisotropies in the explosion, or may have been acquired during the remnant's expansion through interactions with over-densities in the surrounding medium. Notably, an asymmetry was observed in the line of sight, with the northern region predominantly blueshifted and the southern region redshifted, though consensus on its origin remains elusive. To address this question, we conduct a spatially resolved spectroscopic study on 200 regions of Tycho's SNR, as interactions are expected to leave traces in the physical properties of the plasma. A key aspect of this work is the utilization of the nested sampling Bayesian framework BXA to fit complex models, enabling exploration of the entire likelihood landscape and providing posterior distributions for each parameter. Consequently, we obtained 19 parameter maps (including temperatures, ionization times, and abundances) whose scientific potential extends beyond the asymmetry in dynamics. For example, the abundance maps of the intermediate mass elements are compared with nucleosynthesis numerical simulations. In addition, these results reveal for the first time maps of the power law synchrotron index and the potential emission of oxygen line across the entire remnant. Moreover, they offer insights into the physics of the progenitor system, by characterizing local interactions of the remnant with the circumstellar medium and by providing direct information on the explosion's anisotropy. Furthermore, these maps enable the generation of realistic simulations for the XRISM observations of the remnant, preparing for challenges such as the impact of spectral-spatial mixing on scientific objectives in XRISM data.

The multi-layer structure of SNR 1181 with a white dwarf in its center

Poster

Takatoshi Ko

The University of Tokyo, Japan

Abstract

A historical supernova 1181 is a type Iax supernova that is thought to be caused by a binary white dwarf merger. Interestingly, inside of this supernova remnant, a massive white dwarf was found. Optical observations reveal that, from this white dwarf, the very fast wind of about 15,000 km/s is blowing, forming a wind termination shock inside the supernova remnant by colliding with the supernova ejecta. The gases shocked by both the termination shock and the outer supernova remnant shock are expected to be sources of luminous X-ray emission. We constructed a theoretical model for the time evolution of both shocked regions, and compared it with the multi-wavelength observation results. In this talk, we report the structures of the multi-layer SNR and its implications for future observations.

JWST Observations of the Cassiopeia A Supernova Remnant: Near-Infrared Colors of Supernova Ejecta

Poster

Bon-Chul Koo[1], J.-J. Lee[2], D. Milisavljevic[3], R. Fesen[4], and J. Raymond[5]

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[2]Astronomy and Space Science Institute, Korea
[3]Purdue University, USA
[4]Dartmouth College, USA
[5]CfA, USA

Abstract

The young supernova remnant Cassiopeia A was observed by the James Web Space Telescope (JWST) under the Cycle 1 General Observers (GO) Program (ID: 1947, PI: Milisavljevic). The entire remnant has been mapped in near- and mid-infrared by using NIRCam and MIRI, and additionally, exploratory positions that can sample ejecta and circumstellar medium was observed with NIRSpec and MIRI/IFU. These observations reveal intricate details of the supernova ejecta and circumstellar medium that were not previously seen. We have explored the NIRCam F162M, F356W, and F444W images to study the physical and chemical properties of compact ejecta knots moving much faster than other ejecta material. It has been known that these knots are composed of newly-synthesized heavy elements, indicating that they are dense knots expelled from the inner layers of supernova during the explosion. The NIRCam images reveal numerous ejecta knots, most of which are > 1" and often closely clustered together. We derived their NIRCam fluxes and analyzed their colors using NIRSpec spectra as a reference. We also examined the NIRCam colors of the unshocked ejecta in the interior. This poster presentation highlights our preliminary results.

On emission measures and element densities and masses inferred from XSPEC

Poster

Denis Leahy[1], A. Fosterand[2], and I. Seitenzahl[3]

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[3]UNSW, Canada

Abstract

We analyze the assumptions used in XSPEC for calculation of emission measures, and resulting densities and masses of different elements used in fitting X-ray spectra of hot plasmas. For different assumptions of solar abundances, corrections of a few percent are needed. However for hydrogen poor plasmas corrections by factors of several to a few tens are required in interpreting emission measures, densities and masses.

Models for supernova remnants with reverse shock emission

Poster

Denis Leahy

University of Calgary, Canada

Abstract

The interpretation of emission measures (EM) depends on the composition of the shocked plasma. The correct calculations of EM for hydrogen poor plasmas have now been developed, allowing significant improvement of interpretation of plasma properties compared to previous work. With the new calculations, the reverse shock properties of supernova remnants (SNRs) can be interpreted. We carry out these calculations for a set of SNRs with observed reverse shock emission, and discuss the results and their implications for the properties of the SNR population.

Thermal X-ray emission from supernova remnants in 3D (M)HD simulations

Poster

Ekaterina Makarenko and Stefanie Walch

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Abstract

Each supernova (SN) injects around 10^{51} ergs into the interstellar medium (ISM), shaping the ISM's chemical, thermal and dynamic evolution. Around 70% of the injected energy is subsequently lost by radiative cooling. However, the fate of the emitted cooling photons is usually neglected in simulations as the surrounding ISM is treated to be optically thin with respect to it. This makes the high-resolution simulations quite unphysical. As for the actual observations of SN remnants (SNRs): with the growing ability of X-ray imaging spectroscopy, we can define the pixel-by-pixel based parameters (such as plasma temperature, ionization state, and abundance of different elements). Thus, right now, we need more realistic simulations of SNRs. We present state-of-the-art (magneto)hydrodynamic simulations of SN explosion in the inhomogeneous environment using the FLASH code, which considers radiative cooling from the SN event. Radiative cooling is calculated on the fly and is fully consistent with the code's radiative transfer, X-ray physics, and chemistry. We calculate synthetic maps of the simulated SNR in several X-ray energy bands (e.g. Chandra or XRISM energy bands in the range 0.1-10 keV) as well as for selected iron lines. Therefore, synthetic X-ray maps provide unique information about the physics of shock/cloud interaction, general morphology of the remnants, and enhanced magnetic field, as well as a better comparison (and prediction) for SNR observations.

Measurement of anisotropies in observed Supernova Remnants and their interpretation using hydrodynamical models

Poster

Soham Mandal, P. Duffell, A. Polin, and D. Milisavljevic

Purdue University, USA

Abstract

Supernova remnants (SNRs) exhibit varying degrees of anisotropy, which have been extensively modeled using numerical methods. We implement a technique to measure anisotropies in SNRs by calculating power spectra from their high-resolution images. To test this technique, we develop 3D hydrodynamical models of supernova remnants and generate synthetic x-ray images from them. Power spectra extracted from both the 3D models and the synthetic images exhibit the same dominant angular scale, which separates large scale features from small scale features due to hydrodynamic instabilities. The angular power spectrum at small length scales during relatively early times is too steep to be consistent with Kolmogorov turbulence, but it transitions to Kolmogorov turbulence at late times. As an example of how this technique can be applied to observations, we extract a power spectrum from a *Chandra* observation of Tycho's SNR and compare with our models. Our predicted power spectrum picks out the angular scale of Tycho's fleece-like structures and also agrees with the small-scale power seen in Tycho. We use this to extract an estimate for the density of the circumstellar gas ($n \sim 0.28/\mathrm{cm}^3$), consistent with previous measurements of this density by other means. The power spectrum also provides an estimate of the density profile of the outermost ejecta. Moreover, we observe additional power at large scales which may provide important clues about the explosion mechanism itself.

Molecular formation in the ejecta of SN 1987A based on three-dimensional hydrodynamical models

Poster

Masaomi Ono[1], Takaya Nozawa[2], Shigehiro Nagataki[3], Alexandra Kozyreva[4], Tea Temim[4], Salvatore Orlando[5], Marco Micel[6], Ke-Jung Chen[1]

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Abstract

Recent breakthrough observations of SN 1987A by ALMA (Abellan et al. 2017) have revealed three-dimensional (3D) distributions of carbon monoxide (CO) and silicon monoxide (SiO) in the ejecta of SN 1987A and those are rather non-spherical and lumpy; CO also has a ring-like distribution. However, the formation of molecules in core-collapse supernova ejecta has yet to be understood. In particular, a bipolar-like explosion and matter mixing suggested by our previous studies based on 3D hydrodynamical models (Ono et al. 2020; Orlando et al. 2020) with a binary merger progenitor model of SN 1987A (Urushibata et al. 2018) may affect the formation of molecules through the characteristic distribution of radioactive ^{56}Ni and the seed atoms. Additionally, recent JWST observations (Larsson et al. 2023) have shown a broken dipole-like iron distribution in the ejecta of SN 1987A. Together with the ALMA observations, those may provide insights into the explosion mechanism by comparing those with theories. To understand the molecular formation in the ejecta of SN 1987A and the impact of 3D matter mixing on the formation of molecules, we perform (Ono et al. 2024, accepted for publication in ApJS) molecular formation calculations with one-dimensional (1D) ejecta profiles based on the 3D hydrodynamical models (Ono et al. 2020). It is found that the matter mixing could play a non-negligible role in both the formation and destruction of molecules, in particular CO and SiO, through several reaction sequences including those induced by the decay of radioactive ^{56}Ni (^{56}Co). Our models may qualitatively be consistent with the ring-like distribution of CO revealed by ALMA; however, the application to the whole regions of the 3D hydrodynamical models is necessary in the near future.

Morphology and Metallicity: The Supernova Remnants of the Small Magellanic Cloud

Poster

Sonja Panjkov, K. Auchettl, L. Lopez, T. Holland-Ashford, and E. Ramirez-Ruiz

The University of Melbourne, Australia

Abstract

Supernova remnants provide a unique opportunity to greatly increase the number of supernova explosions with progenitor constraints. In the past, this has been done by comparing measured ejecta abundances to theoretical models, or by detecting light echoes from the original event. However, as Type Ia remnants are more spherical and mirror-symmetric than Core-Collapse (CC) remnants, an alternative approach uses the asymmetries in the X-ray emission to classify SNRs as either CC or Type Ia. By applying the Power Ratio Method from Lopez et al. (2009) to the population of SNRs in the Small Magellanic Cloud, we quantify the level of asymmetry in the X-ray emission, allowing us to predict the likely SN type for each remnant. In addition, we investigate how metallicity affects SNR morphology by comparing the SMC results to the galactic and LMC populations.

Investigation of supernova remnant IC 443 and G189.6+3.3 with LAMOST

Poster

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Astrophysikalisches Institut und Universitäts-Sternwarte Jena, Germany

Abstract

We present the results from a study of the optical emission associated with supernova remnant (SNR) SNR G189.6+3.3 and IC 443 based on the spectra from the Large sky Area Multi-Object fiber Spectroscopic Telescope (LAMOST). All available spectra for SNR G189.6+3.3 and IC 443 were used. Dominant Hα, [S II] and forbidden lines for SNRs were detected and measured from the low continuum level (S/N<10) stellar spectra. An average [S II]$\lambda\lambda$6716/6731 to H$\alpha\lambda$6563 ratio of [S II]/Hα= 0.59$\pm$0.02 was found for the northeastern (NE) and eastern (E) regions outside of IC 443, while [S II]/Hα=1.25$\pm$0.03 was found within and slightly outside of IC 443. [S II]/Hα ratios as high as 1.33 are also detected outside the bright filaments of IC 443, indicating that true size might be larger. The electron density (Ne) varies between 4 to 1257 cm^{-3} throughout the whole region, indicating the ionized gas heated by shock. In addition, the shock velocity, the reddening and the interstellar extinction coefficient were calculated and compared with the theoretical values. SNR G189.6+3.3 and IC 443 environments and optical parameters are discussed.

Cloud Formation by Supernova Implosion

Poster

Leonard Romano, M. Behrendt, and A. Burkert

Ludwig-Maximilians-Universität München, Germany

Abstract

The deposition of energy and momentum by supernova explosions has been subject to numerous studies in the past few decades. However, while there has been some work that focused on the transition from the adiabatic to the radiative stage of a supernova remnant (SNR), the late radiative stage and merging with the interstellar medium (ISM) have received little attention. Here, we use three-dimensional, hydrodynamic simulations, focusing on the evolution of SNRs during the radiative phase, considering a wide range of physical explosion parameters ($n_{\mathrm{H,\ ISM}} in\, [0.1, 100]\,\mathrm{cm}^{-3}$ and $E_{\mathrm{SN}} in\, [1, 14] \times 10^{51}$ erg). We find that the radiative phase can be subdivided in four stages: A pressure driven snowplow phase during which the hot overpressurized bubble gas is evacuated and pushed into the cold shell, a momentum conserving snowplow phase which is accompanied by a broadening of the shell, an implosion phase where cold material from the back of the shell is flooding the central vacuum and a final cloud phase, during which the imploding gas is settling as a central, compact overdensity. The launching timescale for the implosion ranges from a few 100 kyr to a few Myr, while the cloud formation timescale ranges from a few to about 10 Myr. The highly chemically enriched clouds can become massive ($M_{\mathrm{cl}} \sim 10^3 - 10^4\,\mathrm{M}_{\odot}$) and self-gravitating within a few Myr after their formation, providing an attractive, novel pathway for supernova induced star and planet formation in the ISM

Probing Shocked Ejecta in SN 1987A: A novel diagnostic approach using XRISM-Resolve

Poster

Vincenzo Sapienza

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Abstract

Supernova (SN) 1987A emerges as a prime candidate for harnessing the capabilities of the newly launched XRISM satellite, due to its fast evolving spectral features. Indeed, this celestial object presents a unique opportunity to delve into the evolution of a supernova into a young supernova remnant. Historically, X-ray emission from SN 1987A has been predominantly attributed to the shocked circumstellar medium (CSM), with no definitive detection of shocked ejecta. However, recent studies compellingly suggest that in the forthcoming years, the X-ray emission from SN 1987A will increasingly originate from the ejecta. Our aim is to assess the proficiency of XRISM-Resolve high resolution spectrometer in pinpointing signatures of the shocked ejecta in SN 1987A. Leveraging a state-of-the-art magneto-hydrodynamic 3 Dimensional simulation that self-consistently describes the transition from the explosion into its remnant, we synthesized the XRISM-Resolve spectrum of SN 1987A and compare the results obtained with and without including the effects of the closed gate valve. Our simulation reflects the expected data during the performance verification phase, scheduled for 2024, but we also explore different exposure times. Our predictions distinctly reveal the prominent role of shocked ejecta in shaping the emission lines' profiles. The Doppler broadening associated with the bulk motion along the line of sight of the rapidly expanding ejecta is shown to increase the line widths well above the values observed so far. The quantitative comparison between our synthetic spectra and the actual XRISM spectra will enable us to establish a robust connection between the broadened line emission and the recently shocked ejecta. This correlation, in turn, will facilitate the extraction of valuable insights into the dynamics and chemical composition of the ejecta through the analysis of X-ray emission data.

New analytical solutions for supernova shocks

Poster

Nina Sanches Sartorio, Florian Kirchschlager, Ilse De Looze, Tassilo Scheffler

Ghent University, Belgium

Abstract

The reverse shock in supernova remnants is the main culprit behind the destruction of all of the newly formed dust in the supernova's ejecta. Multiple studies over the past decade have looked at the dust destruction by the reverse shock with little consensus reached on whether most of the dust gets destroyed. Part of the reason for this disparity is the usage of a different combination of dust destruction mechanism and dust properties in each study. However even studies with similar accounts of dust and its processing seem to give inconsistent results. This in turn has to do with the underlying analytical model that is used to set up many of these simulations. Most papers rely on the seminal work of Truelove & Mckee (1977) in which the ejecta is formed of a core and an envelope region. In particular, the evolution of the envelope are dictated by a parameter 'n' which determines the velocity and density distribution within the region. Because the evolution of the envelope is closely related to the formation and development of the reverse shock, different values of 'n' can lead to significantly different amounts of dust being destroyed. In addition, as this index does not directly tie in to a physical property of the supernovae, it is difficult to know which value it should have. While the value can be adjusted to reproduce the current observed reverse shock properties, that does not guarantee that the past or future evolution of the shock would be accurately described by the model. Furthermore, because this modeling of the analytical solution a reverse shock will always form, even though that should not occur for supernovae surrounded by extremely low density environments. In this work we put forth a new analytical solution to the evolution of supernova remnants which relies solely on physical parameters of the supernova explosion (explosion energy, mass of the progenitor star) and physical properties of the surrounding circumstellar medium (density and temperature). By taking this approach we can predict in a more realistic way when the reverse shock will form (if at all) and how it will evolve over time. This opens the door for more physically based simulations which are, thus, easier to compare and contrast to observations..

Evolution of X-ray Gas in SN 1987A from 2007 to 2021: Ring Fading and Ejecta Brightening Unveiled through Differential Emission Measure Analysis

Poster

Lei Sun[1], S. Orlando[2] E. Greco[2,3] M. Miceli[2], J. Vink[3], P. Zhou[4], and Y. Chen[4]

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Abstract

SN 1987A provides us a unique opportunity to study in detail the birth and the early evolution of the supernova remnant. In this work, we performed a comprehensive differential emission measure analysis on the X-ray emitting gas in SN 1987A from 2007 to 2021 based on XMM-Newton RGS and EPIC-pn observations. We obtained the continuous temperature distribution of SN 1987A and followed its up-to-date evolution. Our results make it possible to compare the observed temperature structure directly with those predicted by MHD simulations, and by doing that we found an excellent consistency between observations and simulations. Based on this consistency, we identified a recently brightening of the reverse-shock-heated ejecta component and confirmed the fading of the ER. The brightening ejecta component is further evident by a recent decline of the Fe K line centroid energy. Additionally, we found a high O VII G-ratio and a high O VIII Lyβ/Lyα ratio in SN 1987A, which is most likely originated from the absorption of the foreground hot gas in Galactic halo.

Simulated non-thermal emission of the supernova remnant G1.9+0.3

Poster

Juan C. Toledo-Roy[1], D. O. Gómez[2], P. F. Velázquez[1], D. M.-A. Meyer[3], A. Chiotellis[4], A. C. Raga[1], A. Esquivel[1], J. C. Toledo-Roy[1], K. M. Vargas-Rojas[1]

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Abstract

Supernova remnants are the nebular leftover of defunct stellar environments, resulting from the interaction between a supernova blastwave and the circumstellar medium shaped by the progenitor throughout its life. They display a large variety of non-spherical morphologies such as ears that shine non-thermally. We have modelled the structure and the non-thermal emission of the supernova remnant G1.9+0.3 through 3D magnetohydrodynamic numerical simulations. We propose that the peculiar ear-shaped morphology of this supernova remnant results from the interaction of its blast wave with a magnetized circumstellar medium, which was previously asymmetrically shaped by the past stellar wind emanating from the progenitor star or its stellar companion. We created synthetic non-thermal radio and X-ray maps from our simulated remnant structure, which are in qualitative agreement with observations, forming ears on the polar directions. Our synthetic map study explains the discrepancies between the measured non-thermal radio and X-ray surface brightness distributions assuming that the inverse Compton process produces the observed X-ray emission.

A method for determination of evolutionary status of supernova remnants from radio data

Poster

Dejan Urošević

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Abstract

A method for determination of evolutionary status of supernova remnants (SNRs) is presented. The phase of SNR evolution can be approximately determined by using radio observation data. The details of this method can be found in Urošević (2020, 2022). For several new detected Galactic and extragalactic SNRs from the nearby galaxies in radio, the evolutionary status was determined and presented here. On the other hand, the model was tested for SNRs for which we know evolutionary status, and the agreements are very well, and also the results of these tests are presented here.

Nebular Phase Stripped Envelope Supernovae in 3D

Poster

Bart van Baal[1], A. Jerkstrand[1], A. Wongwathanarat[2], and T. Janka[2]

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[2]MPIA Garching, Germany

Abstract

Core-collapse supernovae are asymmetric by nature, and in recent years the multi-dimensional modelling of the explosions themselves has made significant progress. Some of these models have been simulated long enough for the ejecta to have become free-coasting. This allows for the evolution of these ejecta into the late-time nebular phase (months after the explosion) by homologous expansion. The asymmetries caused by the explosion are encoded into the line profiles which appear in the nebular phase when the ejecta have become transparent and the spectra are dominated by emission lines. `ExTraSS` (EXplosive TRAnsient Spectral Simulator) is a 3D NLTE spectral synthesis code which is designed to create spectra for supernovae in the nebular phase. The code uses modern multi dimensional explosion models as input and evolves them into the nebular phase. It calculates the energy deposition from the radioactive decay of ^{56}Ni $\rightarrow^{56}$Co $\rightarrow^{56}$Fe and uses this energy deposition to determine the Non-Local Thermodynamic Equilibrium (NLTE) temperature, ionization and excitation structure across the nebula. These physical conditions are then used to generate spectra which vary with viewing angles, creating line profiles with varying centroid shifts and line widths. `ExTraSS` enables the study of line profiles of different elements from the same model and how they differ under changes of viewing angles, as well as comparing between different models. In this talk I will highlight the results from a suite of nine different input models (varying masses and explosion energies of stripped-envelope progenitors; i.e. stars without a hydrogen envelope, exploded with `Prometheus-HotB`) and how the line properties in our models compare to observations and what we can learn about our explosion models through these comparisons. I will also showcase some NIR spectral predictions and outline the future targets for `ExTraSS`.

Study of non-thermal emission of Kepler's SNR with MHD numerical simulations

Poster

Karla M. Vargas-Rojas[1,2], P. F. Velázquez [1,2], and J. C. Toledo-Roy[1]

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[2]UNAM, Mexico

Abstract

A remarkable feature of Kepler's supernova is its ear-like protrusions; however, it is still unclear what causes this notably asymmetric morphology. Several works have attempted to explain the origin of this type of morphology in supernova remnants (SNR). For example, Chiotellis et al. (2020) propose that Kepler's supernova exploded inside a planetary nebula (PN) formed by the interaction of the fast wind from the central White Dwarf (WD) star and the previous slow wind from the AGB star. On the other hand, Tsebrenko and Soker (2013) present a model in which they suggest that the "ears" could have been formed by the interaction of two narrow and opposite jets launched during the merger phase in the core-degenerate scenario for Type Ia explosions with the surrounding ejected nebula. In our study, we further explore combinations of the ideas given by Chiotellis et al. (2020) and Tsebrenko & Soker (2013). We propose that the morphology of Kepler's SNR is due to the presence of a precessing jet launched by the accretion disk produced by the exchange of matter between the AGB and the WD stars just before the SN explosion, and that this occurs within a planetary nebula-like structure produced by the interaction of the slow wind from the AGB star and the fast wind of the WD star. We use the GUACHO numerical code to make 3D magnetohydrodynamic numerical simulations of this scenario to compute synthetic maps of non-thermal emission in X-rays (through the inverse Compton mechanism) as well as in radio (synchrotron) and compare our results with the observations.

Session 5.

Shock Physics, Particle Acceleration, Polarization in SNRs and PWNe – Oral Talks

X-ray polarimetry of supernova remnants with IXPE: puzzling magnetic-field geometries and high levels of downstream turbulence

Invited Talk

Jacco Vink

Anton Pannekoek Institute/GRAPPA, University of Amsterdam, Netherlands

Abstract

The Imaging X-ray Polarimetry Explorer (IXPE) was successfully launched in December 2021. IXPE is the first X-ray satellite mission dedicated to X-ray polarization measurements with an imaging resolution of ∼25". For supernova remnants (SNRs) this in particular important to probe the magnetic field configurations in young SNRs, which emit X-ray synchrotron radiation from >10 TeV electrons. These relativistic electrons are only present near the acceleration sites, as they lose their energy rapidly. The acceleration also needs a high level of magnetic field turbulence, in order to accelerate electron fast enough . So X-ray synchrotron emission comes from near the shock regions, unlike radio synchrotron radiation. It is long known from radio synchrotron polarization measurements that young SNRs have radially oriented magnetic fields, whereas older SNRs have tangentially oriented magnetic fields. The origin of the radial magnetic fields in young SNRs is not well understood.

So the prime science for IXPE observations of young SNRs are: 1) what is the level of magnetic-field turbulence close to the shocks, given the turbulence needed for fast acceleration? 2) what is the magnetic-field topology close to the shocks, where a priori we expect tangential magnetic fields at the shock itself?

IXPE has observed now a number of SNRs: Cas A, Tycho's SNR, SN 1006 (NE), RX J1713.7-3946, RCW 86, and RX J0852-4622. We will summarize the results, and place it in the context of theories magnetic-field turbulence generation, and theories about the origin of radially orientation of magnetic fields in young SNRs. The results published so far indicate a high level of turbulence, i.e. low polarization degrees. For Cas A, Tycho's SNR, and SN 1006 the magnetic fields are radially oriented, hinting that the mechanism for radial field alignments must happen close to the shock, and not at the contact discontinuity. We will also show and discuss new results on RX J1713.7-3946, RCW 86, and RX J0852-4622.

Synchrotron polarization with a partially random magnetic field: general theory, and applications to IXPE observations of young supernova remnants

Oral Talk

Rino Bandiera[1] and Oleh Petruk[2]

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[2]INAF - Osservatorio Astronomico di Palermo, Italy

Abstract

We present here a generalization of our former work, in which analytic formulae have been derived for the synchrotron polarization, in the case of a power-law particle energy distribution in a magnetic field with ordered and random components, to cases where the electron spectrum has a smooth cut-off. Our goal is to develop a prescription for X-ray synchrotron polarization. No analytic expression could be calculated for the general case, so we have devised an efficient numerical method to compute a vast variety of situations. In particular, we have extended the treatment to power-law particles distributions with an exponential, or super-exponential cutoff. In this case we have verified that our former analytic formulae, if applied to a power law approximating a limited spectral range, could be still used as good approximations (underestimating the polarization degree by no more than 0.01) to distributions with a cutoff, for all reasonable choices of cutoff shapes in X-ray spectra of supernova remnants. We have finally treated the more general magnetic field combination of an ordered component and an anisotropic random component. Having in mind supernova remnant forward shocks, we have applied these results to the case of an oblique shock moving in a region with partially random field. We also report application of our findings to three remnants observed by IXPE and derive some conclusions about physical conditions which provide X-ray polarized photons there.

JWST NIRCam observations of Supernova 1987A – shocks, synchrotron and dust

Oral Talk

Mikako Matsuura[1] & JWST/NIRCam team

[1]Cardiff University, United Kingdom

Abstract

At the distance of 50 kpc, Supernova (SN) 1987A is the nearest supernova explosion detected in 400 years, hence, is an ideal target to study how a supernova remnant evolves in time in a very early stage of supernova remnant. We present the JWST NIRCam results of SN 1987A. The SN ejecta expand at 20,000-10,000 km s^{-1} which corresponds to 0.008-0.04 arcsec per year. With an angular resolution 0.06-0.1$''$, NIRCam can spatially resolve the current shocked regions and the aftermath of what the shocks left behind. JWST NIRCam detected synchrtron and dust emission in the ring and its outside, clearly indicate the interaction of the circumstellar material and outer ejecta. The power law index of synchrotron radiation changes at near-infrared wavelengths in the post-shocked regions, showing that high-energy particles die out in time in post-shocked regions. This is an excellent opportunity to study particle acceleration in SNe. Dust thermal emission is also detected but only in the limited regions with intense ongoing shocks. This shows that the cooling time scale of dust grains is probably a few years time scale, quite a short time, even shorter than synchrotron radiation cooling time scale, which could be ten-year time scale. NIRCam found a new feature, crescents, which could trace either reverse shocks falling inwards into the ejecta or X-ray dissociation front of the ejecta. JWST opened a new insight into shock physics in a supernova remnant.

Evolution of magnetic field structure in SN1987A

Oral Talk

Oleh Petruk[1,2], Salvatore Orlando[1], Vasyl Beshley[2], Marco Miceli[3], and Fabrizio Bocchino[1]

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[2] IAPMM, Ukraine
[3] Università degli Studi di Palermo, Italy

Abstract

The remnant of supernova SN1987A undergoes regular observations across various spectral bands. The proximity of a very young SNR makes it possible to conduct spatially resolved analysis. The continuous monitoring conducted over the years records the metamorphosis of a SN into a SNR. This provides us with the unique opportunity to probe the magnetic field in the immediate surrounding of a dying star. Our study presents extensive 3D MHD simulations describing the evolution from the SN event to the current age of SN1987A that yield a numerical representation of the radio history of SN1987A. Specifically, the model accurately reproduces the radio light curve, captures the sequence of observed radio images spanning several decades, and provides a polarization map at the 30-year post-explosion age similar to that observed by the Australia Telescope Compact Array. Then, we reconstruct the progression of East-West asymmetry in both polarized and unpolarized images, along with changes in the distribution of polarization vectors across the surface of SN1987A through the years. In this way, we reconstruct the development of the magnetic field structure within the remnant and probe its distribution in the circumstellar medium before the occurrence of the supernova explosion. This gives us the opportunity to investigate the final phases, including magnetic activity, in the evolution of the progenitor star.

Pulsar Wind Nebulae in the light of the new IXPE observations: putting our understanding to the test

Invited Talk

Niccolo Bucciantini

INAF - Osservatorio Astrofisico di Arcetri, Italy

Abstract

With the IXPE satellite a new observational window has opened for the study of the physical properties of Pulsar Wind Nebulae. For the first time we are able to directly map the magnetic field geometry in the inner regions of these systems, where our current theoretical models place the site of particle acceleration. I will review the current status of X-ray polarimetry in PWNe, in the context of the canonical PWN picture, and how it relates to information from other wavelengths. Implications for the physics of acceleration, and the role of turbulence, will be also discussed.

Particle Acceleration at SNR shocks: Bridging Simulations and Observations

Oral Talk

Damiano Caprioli

University of Chicago, USA

Abstract

First-principles plasma simulations have been pivotal in helping developing a theory of ion and electron acceleration at shocks, and in particular in SNRs. I discuss what we have learned about particle spectra and maximum energy, the dependence of acceleration efficiency on the shock strength and inclination, and the relative injection of ions and electrons. These ingredients are crucial to model the multi-wavelength emission from SNRs, to unravel the hadronic/leptonic nature of their gamma-ray emission, and to assess their role of sources of Galactic cosmic rays.

Electron-Ion Equilibration and Cosmic Ray Acceleration in two Balmer-Dominated SNRs

Oral Talk

Parviz Ghavamian[1], John C. Raymond[2], and Ivo Seitenzahl[3]

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[2] Harvard-Smithsonian Center for Astrophysics, USA
[3] University of New South Wales (UNSW), Canberra, Australia

Abstract

Balmer-dominated supernova remnants present one of the rare opportunities to study how electrons and ions are heated in collisionless shocks. With enough observational constraints, it is also possible to probe how much shock energy is channeled into cosmic rays (CRs). Here we combine results from HST and MUSE integral field spectroscopy of two Balmer-dominated supernova remnants, SNR 0509-67.05 and SNR 0519-69.0, in the LMC, to place new constraints on electron-ion equilibration up to $v_{sh} \sim 7000$ km/s. The HST proper motions in both objects extend over at least 10 years, providing excellent constraints on shock speeds at numerous locations along the entire rim of both SNRs. These measurements can be simultaneously matched to broad H$alpha$ widths measured from the MUSE data, allowing us to use theoretical models to estimate T_e/T_p . While many shock positions in both SNRs show $T_e/T_p \lesssim 0.1$, many others show Hα FWHM that are too low for even full equilibration. Absent any corresponding evidence of electron temperature fluctuations from X-ray data, we explore the role of non-Maxwellian (nonthermal) contributions to the wings of the broad Hα profile, resulting from, e.g, efficient CR acceleration. Our results suggest that in some locations more than 20% of the shock energy may be channeled into CRs.

Acceleration an release of electrons from supernovae remnants

Oral Talk

Giovanni Morlino

INAF, Italy

Abstract

The process that allows cosmic rays (CRs) to escape from their sources and be released into the Galaxy is still largely unknown. The comparison between CR electron and proton spectra measured at Earth suggests that electrons are released with a spectrum steeper than protons. Assuming that both species are accelerated at supernova remnant shocks, we here explore two possible scenarios that can in principle justify steeper electron spectra: (i) energy losses due to synchrotron radiation in an amplified magnetic field and (ii) time-dependent acceleration efficiency. We show that both mechanisms are required to explain the electron spectrum. In particular, synchrotron losses can only produce a significant electron steepening above ∼1 TeV, while a time-dependent acceleration can explain the spectrum at lower energies if the electron injection into diffusive shock acceleration is inversely proportional to the shock speed. We discuss observational and theoretical evidence supporting such a behaviour.

SNRs in their Golden Years: Predicting the Bright, Nonthermal Signatures of Radiative Shocks

Oral Talk

Rebecca Diesing[1], Minghao Guo[2], Chang-Goo Kim[2], James Stone[3], and Damiano Caprioli[4]

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[2]Princeton University, USA
[3] Institute for Advanced Study, USA
[4]University of Chicago, USA

Abstract

The end of supernova remnant (SNR) evolution is characterized by a so-called "radiative stage" in which efficient cooling of the hot bubble inside the forward shock slows expansion, leading to eventual shock breakup. Understanding SNR evolution at this stage is vital for predicting feedback in galaxies, since SNRs are expected to deposit their energy and momentum into the interstellar medium at the ends of their lives. A key prediction of SNR evolutionary models is the formation at the onset of the radiative stage of a cold, dense shell behind the forward shock. However, searches for these shells via their neutral hydrogen emission have had limited success. We instead introduce an independent observational signal of shell formation arising from the interaction between nonthermal particles accelerated by the SNR forward shock (cosmic rays) and the dense shell. Using a semi-analytic model of particle acceleration based on state-of-the-art simulations coupled with a high-resolution hydrodynamic model of SNR evolution, we predict the nonthermal emission that arises from this interaction. We demonstrate that the onset of the radiative stage leads to nonthermal signatures from radio to gamma-rays, including a radio and gamma-ray brightening by nearly two orders of magnitude. Such a signature may be detectable with current instruments, and will be resolvable with the next generation of gamma-ray telescopes (namely, the Cherenkov Telescope Array).

Shock-Cloud Interactions in Supernova Remnants Revealed by ALMA

Oral Talk

Hidetoshi Sano

Gifu University, Japan

Abstract

Our presentation aims to provide a comprehensive review of recent observational findings concerning shocked interstellar medium (ISM) clouds associated with supernova remnants (SNRs) by using ALMA. Leveraging multiwavelength studies, we uncover not only the properties of shock-heated and ionized mediums but also shed light on the high-energy physical processes occurring within dozens of Galactic and Magellanic SNRs. The interaction between shocks and clouds amplifies turbulent magnetic fields up to milli-Gauss levels, leading to distinctive features such as synchrotron X-ray limb-brightening along cloud surfaces and rapid flux variations in X-rays. Moreover, the high-energy cosmic-ray electrons may be efficiently accelerated in the reflected shocks. Spatially resolved X-ray spectroscopy, coupled with cloud distribution analysis, plays a pivotal role in unraveling the spatial variability of thermal plasma and relativistic particle conditions. An estimation of the total energy carried by accelerated cosmic-ray protons is feasible through a comparison between the hadronic gamma-ray luminosity and the density of shocked gas. Additionally, we will delve into practical methodologies for identifying associated interstellar clouds and discuss the promising avenues of SNR research leveraging radio, gamma-ray, and X-ray observations. Through this presentation, we aim to provide insights into the intricate dynamics and energetics of shock-cloud interactions within the context of SNRs, offering valuable perspectives for advancing our understanding of cosmic-ray acceleration mechanisms and the broader evolution of interstellar environments.

Session 5.

Shock Physics, Particle Acceleration, Polarization in SNRs and PWNe – Posters

How I learned to stop trusting my X-ray spectral best fits and love nested sampling

Poster

Fabio Acero

AIM CEA Saclay, France

Abstract

With more than two decades of X-ray archival data, the X-ray space telescopes Chandra and XMM-Newton provide highly detailed spectra of many SNRs. The spectral modeling of such exquisite datasets requires complex models, often with a large number of degrees of freedom ($N_{\text{parameters}} > 10$). For such models, we will show that the defaults fitting methods included in Xspec, Sherpa or SPEX (the most used fitting packages) are not robust to the initialization points and are prone to stop in local minima, strongly limiting the interpretability of the results. To showcase this effect we have run a small data challenge by making public a fake spectrum of a representative toy model of the Tycho SNR (SN 1572). This dataset will be circulated in the X-ray community, including recognized SNR experts in this field, and the best-fit results will be collected for a comparison with the simulated ground truth and the complete likelihood landscape to get a better insight of traditional fitting method failure. This poster will present the results of this crowd-fitted data challenge to highlight the diversity of results that can be obtained when using different starting points and hand made methods to help the fit to converge. The issue of robust convergence with current widely used tools might be an issue that has been globally overlooked and could be a bottlenecks in reproducible science for SNR in X-rays. If the fit stops in a local minima, the reported errors on the parameters and associated science might be inaccurate. This issue might become important with the high spectral resolution data from the XRISM microcalorimeter and future mission such as LEM or Athena. A comparison with modern alternative fitting methods such as Markov Chain Monte Carlo and Nested Sampling will be displayed. In particular the Nested Sampling technique is showed to accurately recover the correct solution and is independent of any initialization point and should be included in our X-ray spectral toolkit.

Radio Polarization Studies of Galactic Supernova Remnants with ASKAP

Poster

Brianna Ball

University of Alberta, Canada

Abstract

EMU (Evolutionary Map of the Universe) and POSSUM (Polarization Sky Survey of the Universe's Magnetism) are ongoing radio sky surveys being conducted with the Australian Square Kilometre Array Pathfinder (ASKAP) that will cover most of the Southern sky. The superior resolution and sensitivity of these surveys, when compared to previous Southern sky surveys, have opened up new opportunities for observations of Galactic SNRs. Early results from EMU and POSSUM have shown that they will be particularly useful for studying large, high-latitude Galactic supernova remnants, which are often not covered in Galactic plane surveys. These remnants are well-suited for studying the radio polarization of Galactic SNRs. I will present early results based on POSSUM observations of the Galactic SNR G278.94+1.35 (nicknamed "Diprotodon"), one of the largest known SNRs in our Galaxy with an angular size of more than 3 degrees. Diprotodon's large angular size, high-latitude, and high degree of polarization make it particularly well-suited to polarization studies and have allowed us to develop novel techniques. By combining RM synthesis with QU-fitting, we are able to separate foreground from internal Faraday rotation. We use background polarized sources from the POSSUM polarization catalogue to probe the magnetic field configuration inside the SNR and estimate a distance based on a comparison with Diprotodon's foreground RM. We also study the ambient magneto-ionic medium structure and compare this with large scale magnetic field models of the Milky Way Galaxy. We determine the magnetic field strength and configuration inside the SNR shells, comparing our results with theoretical models. The results from Diprotodon demonstrate the full potential of the POSSUM survey and will serve as a template for POSSUM polarization studies of Galactic SNRs and polarization studies of radio SNRs in general.

The Expansion and Width of the Synchrotron Filaments Associated with the Forward Shocks of SNRs

Poster

Daniel Castro

Harvard-Smithsonian Center for Astrophysics, USA

Abstract

X-ray observations of Cas A, RCW 86 and HESS J1731-347 have revealed filamentary non-thermal rims tracing the forward shocks of these supernova remnant (SNRs). These structures have been identified as synchrotron radiation from shock-accelerated electrons with TeV energies, interacting with the compressed, and probably amplified, local magnetic field. Magnetic field amplification is broadly believed to result from, and contribute to, cosmic ray acceleration at the shocks of SNRs. Using the data from the repeated Chandra observations of these remnants, we have estimated the expansion of the non-thermal rims at the forward shocks of the SNRs, as well as the width of these filaments. Since the size of the synchrotron filaments places constraints on the magnetic field strength, this study allows us to establish a connection between the shock velocity and the characteristics of the particle acceleration process.

Relativistic MHD turbulence simulations and synchrotron polarization properties of Pulsar Wind Nebulae

Poster

Luca Del Zanna[1], Niccolò Bucciantini[2], and Simone Landi[3]

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[2]INAF - Arcetri, Italy
[3]University of Florence, Italy

Abstract

Pulsar Wind Nebulae, and the Crab Nebula in particular, are among the best laboratories for high-energy astrophysics, where ultra-relativistic electrons are accelerated, synchrotron and Inverse Compton are the dominant emission mechanisms, and for which the IXPE satellite has recently produced X-ray polarimetry maps in the keV range, suggesting a patchy distribution of turbulence with varying properties throughout the nebula. In order to assess them, 2D and 3D numerical simulations of relativistic turbulence in a magnetically dominated plasma are performed with a novel GPU-accelerated version of the ECHO code for special and general relativistic MHD. Aspects such as plasma emission polarization properties, intermittency of turbulence and statistics of reconnection events will be investigated.

X-ray polarimetry of RX J1713.7-394

Poster

Riccardo Ferrazzoli

INAF-Istituto di Astrofisica e Planetologia Spaziali, Italy

Abstract

Recent X-ray polarimetric measurements by the Imaging X-ray Polarimetry Explorer (IXPE) have revealed radial magnetic fields near particle acceleration sites in young SNRs Cassiopeia A, Tycho, and SN 1006. We present here the spatially-resolved IXPE X-ray polarimetric observation of the northwestern rim of SNR RX J1713.7-3946. We found that the magnetic fields in particle acceleration sites of this SNR is oriented tangentially with respect to the shock front. These results are compatible with a shock-compressed magnetic field.Because of the lack of precise Faraday rotation measurements in the radio band, this is the first time that the geometry of the magnetic field of RX J1713.7-394 is mapped. The average measured polarization degree is lower than the one measured by IXPE in SN 1006, comparable to the Tycho one, but notably higher than the one in Cassiopeia A. In order to explain the observed PD, either there is a radial net magnetic field upstream of the shock, or the turbulence is reisotropized downstream by radial magneto-hydrodynamical instabilities. From comparison of PD and magnetic field distribution with gamma-rays and ^{12}CO data, our results provide evidence in favor of a leptonic origin of the gamma-ray emission.

Evidence for proton acceleration and escape from the Puppis A SNR using Fermi-LAT observations

Poster

Roberta Giuffrida[1,2], Marianne Lemoine-Goumard[3], Marco Miceli[1,2], Stefano Gabici[4], Maki Aruga[5], Martin Mayer[6], Hidetoshi Sano[7], and Yasuo Fukui[5]

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[7]Faculty of Engineering, Gifu University, Japan

Abstract

Supernova remnants (SNRs) are the best candidates for galactic cosmic ray acceleration to relativistic energies via diffusive shock acceleration (DSA). The gamma-ray emission of SNRs can provide direct evidence of leptonic (inverse Compton and bremsstrahlung) and hadronic (proton-proton interaction and subsequently pion decay) processes. Puppis A is a $\sim$ 4 kyr old SNR interacting with interstellar clouds which has been observed in a broad energy band, from radio to gamma-ray. We performed a morphological and spectral analysis of 14 years of observations with the Fermi-LAT telescope in order to study its gamma-ray emission. We found a clear asymmetry in high-energy brightness between the eastern and western sides of the remnant, reminiscent of that observed in the X-ray emission. The different spectral shape of the Eastern side, interacting with a molecular cloud, and the Western side, interacting with an atomic cloud, suggests the presence of different cosmic-ray populations. We propose a radiative scenario for the Eastern side, where the shock velocity decreases because of the interaction with a dense ambient medium and DSA for the Western side. Moreover, we analyzed two gamma-ray sources located close to the remnant. The hardness of their spectra suggests that the gamma-ray emission can be due to protons escaping from the shock of Puppis A.

Jitter radiation as an alternative mechanism for the nonthermal emission in Cassiopeia A

Poster

Emanuele Greco[1], Jacco Vink, Amael Ellien, Silvia Perri, Marco Miceli, and Salvatore Orlando

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Abstract

Synchrotron radiation from relativistic electrons is usually invoked as responsible for the non-thermal emission observed in supernova remnants. Diffusive shock acceleration is the most popular mechanism to explain the process of particles acceleration and within its framework a crucial role is played by the turbulent magnetic field. However, the standard models commonly used to fit X-ray synchrotron emission do not take into account the effects of turbulence in the shape of the resulting photon spectra. In this talk I will present the results of the analysis of multi-instrument X-ray observations based on an alternative mechanism that properly includes turbulence effects in such spectra: the jitter radiation. This emission processes leads to a photon spectrum that extends to higher energies compared to the standard synchrotron and provides critical information on the spectral distribution and scale-size of the magnetic turbulence downstream the shock. We found that the jitter model describes the X-ray soft-to-hard range better than any of the standard cutoff models. Being emitted by electrons sensitive to small-scale turbulence, jitter radiation naturally explains the low X-ray polarisation fraction observed by IXPE. Moreover, the jitter radiation allows us to directly measure the index of the magnetic turbulence spectrum νB and the minimum scale of the turbulence lmin across several regions of Cas A, with best-fit values $\sim 2 - 2.4$, slightly steeper than the Kolmogorov spectrum and lower than 100 km, respectively. Finally, I will present future prospects about the application of this scenario to other young synchrotron-dominated SNRs.

Resolving the gamma-ray supernova remnant IC 443 with Fermi LAT and VERITAS

Poster

Jack W. Hewitt, on behalf of the Fermi LAT and VERITAS collaborations

University of North Florida, USA

Abstract

IC 443 is among the closest and best-studied cases of a supernova remnant interacting with a molecular cloud. The gamma-ray spectrum shows evidence of a cutoff at low energies, interpreted as evidence of a hadronic origin. A new Fermi and VERITAS spatially-resolved study from GeV to TeV energies reveals evidence for multiple components contributing to the SNR shell. This allows the first spatially-resolved study of gamma-ray emission from GeV to TeV energies. A spectral break is evident for both the entire remnant and individual regions. The brightest region appears to cutoff near an energy of 1 TeV. We discuss the implications for particle diffusion in this remnant.

Two new radio-dim, gamma-ray-bright supernova remnants

Poster

Jack W. Hewitt[1], S. Kumar[2], and B. Humensky[3]

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[2]University of Maryland, USA
[3]NASA GSFC, USA

Abstract

We report the Fermi-LAT detection of two newly established supernova remnants (SNRs) which belong to a class of radio-faint, yet gamma-ray bright SNRs. SNR G189.6+3.3 overlaps with the smaller and brighter SNR IC 443. The X-ray emission shows a radiative recombining continuum, evidence of an ongoing or past interaction with a dense medium. The gamma-ray emission is extended, matching the size of the SNR in radio and X-rays, with a spectral index of 2. The SNR candidate G107.5-5.2, also named the Nereides Nebula, is detected in [O III] and Hα narrow-band images. Its large 3 degree diameter in optical makes it comparable to the Cygnus Loop, albeit much fainter. It is spatially coincident with the extended gamma-ray source FHES J2304.0+5406. No radio or X-ray emission has yet been detected. Their large gamma-ray extensions are well-matched to the sizes of the SNRs, supporting an association.

Shock geometry and physics in the supernova remnant SNR 0509-67.5

Poster

Sladjana Knežević[1], Rino Bandiera[2], Giovanni Morlino[2] , Steve Schulze[3], John C. Raymond[4], and Glenn van de Ven[5]

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Abstract

We analyzed MUSE/VLT spectroscopic observations of the supernova remnant SNR 0509-67.5 within the Large Magellanic Cloud. Our primary investigation centered on examining the radial and azimuthal Hα-emission profiles. Our findings indicate that the observed radial trends in the broad-component parameters within the northeastern region align with a spherical thin-layer geometric model characterized by high neutral density gradients. However, the shock velocity appears to be lower than what proper motions suggest. Additionally, our analysis reveals that the measured broad-component widths in various locations surrounding the remnant necessitate an understanding of cosmic-ray physics for explanation.

Kinetic-based CFD modeling of synchrotron emission spectra in fast SNRs

Poster

Vladimir Zekovic[1,2], Petar Kostić[3], Bojan Arbutina[1], and Ivan Petraš[1]

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[3]Astronomical Observatory, Belgrade, Serbia

Abstract

Recent kinetic particle-in-cell (PIC) simulations show that high-Mach number collisionless shocks can produce steep electron spectra. Due to short large-amplitude magnetic structures (SLAMS) driven in the upstream region, cosmic-ray (CR) electrons accelerate by a mechanism that is distinctly different from diffusive shock acceleration (DSA). Here we use the insights from the PIC runs together with optical observations to model the radio-synchrotron spectra observed in young and fast supernova remnants (SNRs), which show slopes similar to those from the PIC runs. First, we perform computational fluid dynamics (CFD) simulations of SNR shocks propagating in the homogeneous and clumpy interstellar media. To exclude spectral steepening due to non-linear DSA, we assume unmodified shocks. We then apply our kinetic-based semi-analytical model of particle acceleration with SLAMS to calculate the magnetic fields and CR electron spectra from the fluid velocity obtained at each computational cell of the detected shock. We also introduce a concept of maximum acceleration energy for electrons that depends on the shock Mach number and the strength of the ambient field. Finally, we discuss the influence of inhomogeneities and CR-driven bubbles on the shape and slope of the synchrotron spectra throughout the adiabatic stage of SNR evolution.

A self-consistent model of shock-heated plasma in non-equilibrium states for direct parameter constraints from X-ray observations

Poster

Yuken Ohshiro[1,2], Hiroya Yamaguchi[2], Shunsuke Suzuki[3], and Yoshizumi Okada[3]

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[2]Institute of Space and Astronautical Science (ISAS), Japan
[3]Aoyama Gakuin University, Japan

Abstract

X-ray observations of shock-heated astrophysical plasmas, such as supernova remnants, often indicate the temperature and ionization non-equilibrium features. Considering non-equilibrium conditions is essential to interpret the observations properly. Here we present a self-consistent model of thermal X-ray emission from shock-heated plasmas that takes into account non-equilibrium conditions of temperature and ionization. For a given set of shock speed and initial electron-ion temperature ratio, the temperature and ionization state of each element are calculated by simultaneously solving the relaxation processes of temperature and ionization. The thermal X-ray spectrum is synthesized by combining our model with the AtomDB spectral code and compared with the `nei` model, the constant-temperature non-equilibrium ionization model commonly used in X-ray astronomy. The differences in emission line intensity between the models are large enough to be distinguishable even with the CCD detectors currently used on spacecraft. The comparison between the models indicates that the assumption of constant temperature made in `nei` model introduces a systematic bias of a 30-40% decrease in the estimation of ionization degree. Our model is implemented in the standard software for X-ray analysis, XSPEC, enabling the direct constraint on the physical parameters of shock-heated plasmas from observational data. We apply our model to the archival *Chandra* X-ray dataset of the supernova remnant N132D. Azimuthal shock speed distribution is obtained from spatially resolved spectra along the shock front. The obtained shock speed ranges from $\sim 800\mathrm{km\,s^{-1}}$ to $\sim 1500\mathrm{km\,s^{-1}}$, which are roughly consistent with the previous optical study.

Time evolution of the synchrotron X-ray emission in Kepler's SNR: the effects of turbulence and shock velocity

Poster

Vincenzo Sapienza

INAF - Osservatorio Astronomico di Palermo, Italy

Abstract

Supernova remnants (SNRs) frequently exhibit electron acceleration within their shocks, with the maximum achievable energy constrained by radiative losses. This limitation arises when the synchrotron cooling time scale matches the acceleration time scale. Conversely, the slow speed of a shock propagating through a dense medium is expected to lead to a higher acceleration time scale, leading to a diminished maximum electron energy and nonthermal X-ray flux for a given SNR age. We investigated the case of Kepler's SNR, a young remnant which exhibits a shock evolving within diverse environments, leveraging a spatially resolved spectral analysis in the X-rays. We identified an enhanced efficiency of the acceleration process, approaching the Bohm limit in the north of its shell, where the shock is impeded by a dense circumstellar medium. Prompted by our previous results, we explore in detail the time evolution of the synchrotron flux, taking advantage of the two deepest *Chandra* X-ray observations of Kepler's SNR (performed in 2006 and 2014) and the polarization of the synchrotron emission, by taking advantage of radio observations. We analyzed the spectra of different filaments in the northern shell of the remnant, and measured their proper motion, the non-thermal flux and average polarization fraction. For each region we also estimated the ratio between the acceleration time and the synchrotron cooling time. We found a region with low shock velocity and large acceleration time over cooling time ratio, where we measured a significant decrease in flux from 2006 to 2014, thus being the first evidence of fading synchrotron emission in Kepler's SNR. Our findings are validated by the radio polarization fractions; we indeed retrieved a lower radio polarization fraction in the north of the remnant, associated with a more turbulent magnetic field, hence a lower Bohm factor. Our results display a coherent picture of the different regimes of electron acceleration observed in Kepler's SNR.

The production of unstable cosmic-ray isotopes in supernovae clusters

Poster

Xinyue Shi, and Martin Pohl

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Abstract

Supernovae remnants are known as promising sites for accelerating particles to relativistic energies, offering persistent targets to study cosmic-ray acceleration across various wavebands. The unstable isotope of iron-60 (^{60}Fe), with a half-life of a million years, is produced only in supernova explosions. The observed presence of ^{60}Fe in cosmic rays and its detection in deep-sea crusts and sediments suggest their acceleration either out of the supernova ejecta or out of enriched circumstellar material around the supernova progenitors, indicating cosmic ray production in clusters of supernovae. In our study, we focus on the latter scenario, using the time-dependent acceleration code RATPaC to investigate the spectrum of various isotopes, including protons, and ^{60}Fe, within a local bubble generated by several supernovae in its state right before the last supernova explosion. The transport equation for cosmic rays, and magnetic turbulence in test-particle approximation have been solved simultaneously with the hydrodynamic equations in 1-D spherical symmetry. The evolution of ^{60}Fe mass ratio within the local bubble is also tracked simultaneously and independently using passive scalars. We report our results in realistically characterising the energy spectrum of ^{60}Fe, estimating its abundance, and interpret its observed features among cosmic rays. The insights gained from this study contribute to a deeper understanding of the role of supernovae in cosmic ray origins and acceleration, in particular concerning particle acceleration in the solar vicinity.

Modeling Shock Emission Including Dust Destruction

Poster

Jonathan D. Slavin and John Raymond

Harvard-Smithsonian Center for Astrophysics, USA

Abstract

Emission from radiative and non-radiative shocks in supernova remnants can provide important information about the nature of the medium surrounding the remnant as well as physical processes in the shock. Many models of the emission from such shocks ignore the effects of the presence of dust. We present new models for optical/UV emission in shocks in which dust is destroyed, including the return of dust material to the gas phase and the non-equilibrium ionization of that material.

Reinterpretation of the Fermi acceleration of cosmic rays in terms of the ballistic surfing acceleration in supernova shocks

Poster

Krzysztof Stasiewicz

Space Research Centre, Polish Academy of Sciences, Poland

Abstract

It is shown that the first order Fermi acceleration of cosmic rays, based on a concept of ions reflected by shocks, is a poor man's approximation of the ballistic surfing acceleration (BSA) mechanism. Incidentally, both mechanisms lead to the same expression for the energy gain of a particle after one encounter with the shock, and to the same power-law distribution of the cosmic ray energy spectrum. It is shown that the 'knee' observed in the spectrum at energy of 5×10^{15} eV could correspond to ions with gyroradius comparable to the size of shocks in supernova remnants, and the spectral index is determined by the average magnetic field compression. The BSA mechanism can reproduce accurately the observed index $= -2.5$ below the knee energy as well as a steeper spectrum above the knee. The acceleration time up to the knee implied by BSA is on the order of 500 years. In addition to BSA, it has been established that thermalization, heating, and energization of ions and electrons in collisionless shocks are related to the following plasma processes:

SWE – stochastic wave energization
TTT – transit time thermalization
QAH – quasi adiabatic heating

A Self-regulated Stochastic Acceleration Model of Pulsar Wind Nebulae

Poster

Shuta J. Tanaka[1], and Wataru Ishizaki[2]

[1]Aoyama Gakuin University, Japan
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Abstract

Pulsar wind nebulae (PWNe) are the relativistic magnetized plasma bubbles powered by their central pulsars and show nonthermal radiation spectra from radio through PeV gamma-rays. The classical mysteries of pulsar-PWN physics are sigma- and kappa-problems, i.e., problems for the magnetization and the particle number of the parent pulsar wind plasma created at the parent pulsar magnetosphere. The turbulence inside the PWN would play a role for resolving the problems (for sigma-problem, see Porth et al. 2014; Tanaka, Toma & Tominaga 2018). Here, we study the stochastic particle acceleration by the turbulence inside the PWN in order to resolve the kappa-problem (Tanaka & Asano 2017). We improve our stochastic acceleration model taking into account the evolution of the turbulent energy inside the PWN. The turbulence energy injected from the central pulsar is self-regulated by accelerating the particles and the nebula expansion. The present model can reproduce the broadband (especially radio) emission from the Crab Nebula without (unrealistic) broken power-law particle injection from the pulsar. In this model, accelerated hadrons can be contained inside the PWN and the neutrino signal would distinguish the models.

Suzaku/XIS study of the acceleration environment of bilateral SNR RX J0852.0-4622

Poster

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Abstract

Quantitative evaluation of the contribution of supernova remnants (SNRs) to galactic cosmic rays has been an open question since the discovery of cosmic rays. SNR RX J0852.0-4622 is known to have strong non-thermal X-ray and very-high-energy gamma-ray emissions and efficiently accelerates cosmic rays (Tsuji et al., 2021). For these reasons, it is regarded as an important object for studying cosmic ray acceleration. Numerical simulations suggest that the cause of this efficient cosmic ray acceleration may be due to the surrounding environment as (Scenario 1) the interaction with the shock and galactic magnetic field as reported in SN1006 (Rothenflug et al., 2004, Xu et al., 2022, Zhou et al., 2023), or (Scenario 2) magnetic turbulence by the interaction between the dense cloud and the shock (Inoue et al., 2012) as reported in SNR RX J1713.7-3946 (Sano et al., 2015). However, quantitative evaluation of these effects has not been assessed so far. To examine these two scenarios, we analyzed data from the X-ray astronomy satellite Suzaku/XIS to quantitatively evaluate the spatial variation of the X-ray spectrum. The observed X-rays in the energy range of 2 to 8 keV are well described with the absorbed power-law (TBabs $\times$ power-law) model and can be parameterized with flux and photon index. The X-ray flux showed a bimodal distribution in relation to the azimuthal angle. We found for the first time that the X-ray flux was maximized in a region quasi-parallel to the direction of the Galactic magnetic field estimated from our polarimetric observations of stars in the vicinity of the SNR. This result can be explained by the model in which the number of cosmic-rays injected into the shock region increases when the Galactic magnetic field and the shock-nominal are parallel (Leckband et al., 1989), supporting scenario 1. On the other hand, by comparing the density distribution of molecular clouds swept up by the stellar wind of the progenitor star (Fukui et al., 2017) and gamma-rays (H.E.S.S. Collabo., 2018), for the first time, we obtained the correlation between X-ray flux and cloud density (correlation coefficient in east region: 0.92, and west region: 0.19), the photon index and cloud density (-0.25 in both east and west region) and the very-high-energy gamma-ray flux (east region: 0.84, west region: 0.77). The positive correlation between X-ray flux and cloud density in the west region and X-ray flux and gamma-ray flux in both the east and west regions can be explained by interaction with dense clouds, which slows the shock velocity and changes the cosmic ray injection rate. In this presentation, we report a detailed analysis method and discuss the cosmic ray acceleration environment near the SNR based on our results.

Modeling the supernova remnant RX J1713.7–3946: particle acceleration, gamma-ray emission, and neutrino flux

Poster

Sabina Ustamujic[1], **Roberto Alfano**[2], **Marco Miceli**[2], **Fabrizio Bocchino**[1], and **Salvatore Orlando**[1]

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Abstract

Multiwavelength observations indicate that supernova remnant (SNR) shocks are sites of effective particle acceleration. The case of SNR RX J1713.7-3946 is of special interest in this respect being the brightest TeV gamma-ray and nonthermal X-ray SNR observed. However, the origin of the TeV gamma-ray emission from RX J1713.7-3946 has been a matter of active debate since both hadronic and leptonic scenarios can reproduce the data under certain assumptions so neither of the two scenarios can currently be excluded. Assessing the role of the hadronic emission is crucial to derive constraints on the neutrino emission, which will be observed by the KM3NET neutrino telescope, a deep-sea neutrino telescope optimized for the detection of high-energy neutrinos of cosmic origin. The SNR seems to be evolving in a non homogenous clumpy medium with molecular clouds observed in the vicinity of the source, but a detailed characterization of the remnant and his properties is still missing. We developed a MHD model of RX J1713.7 that follows the evolution of the remnant and its interaction with the complex environment characterized in agreement with the observations. From the model we derive X-ray and gamma-ray maps and spectra that can be directly compared with actual data. Here we present our preliminary results.

Session 6.

SN/SNR dust, environments, feedback – Oral Talks

Supernova dust formation and destruction in the JWST era

Invited Talk

Ilse De Looze

Ghent University, Belgium

Abstract

The large reservoirs of dust observed in some high redshift galaxies have been hypothesised to originate from dust produced by supernovae originating from massive stars. Theoretical models predict that core-collapse supernovae (CCSN) can be efficient dust producers ($0.1 - 1\ M_{\odot}$) potentially responsible for most of the dust production in the early Universe. Observational evidence for this dust production efficiency has been recently obtained through two independent methods: (a) the detection of cold supernova dust emission with Herschel and (b) modelling the red-blue line asymmetries observed for optical lines caused by dust obscuration effects in the supernova ejecta. While dust is known to efficiently form in supernova ejecta, its eventual fate will depend on the processing by the supernova's forward and reverse shocks. In this talk, I will review recent observational and numerical efforts that scrutinise supernova dust formation and destruction in SNRs. In recent times, JWST has delivered a unique view on the small-scale distribution of (un)shocked supernova dust in Galactic supernova remnants. I will give an extensive overview of new JWST observations of Galactic and extragalactic SN/SNRs that focus on analysing the distribution and properties of supernova dust and that track how this dust is being processed by supernova shocks. Finally, I will talk about a puzzling newly identified structure, named the "green monster", that dominates the mid-infrared emission in the central regions of Cassiopeia A. The detection of this dense circumstellar structure in the foreground of Cas A provides important information on the evolution of the progenitor prior to the explosion.

Unraveling Cosmic Dust Origins: JWST Revelations from Supernovae

Oral Talk

Melissa Shahbandeh

Space Telescope Science Institute (STScI), USA

Abstract

Dust has seeded the Cosmos with galaxies, stars, and planets since the Universe was young. Despite its critical role, the origins of this cosmic dust have remained shrouded in mystery. AGB stars were originally considered the primary candidates for dust production, but large dust reservoirs have been observed to exist before AGB stars had time to produce them. Core-collapse supernovae (CCSNe) resulting from the death of massive, short-lived stars, offer an alternative explanation, but prior to JWST, we had no instrument with both the sensitivity and wavelength coverage required to test this theory. The focal point of this presentation will be JWST observations of several CCSNe that span from dust precursors formation to massive dust accumulation decades post-explosion. Previously, measurements of molecular dust precursors and dust reservoirs over five years post-explosion have only been achievable for SN 1987A due to its exceptional proximity. I will present NIRSpec and MIRI early spectroscopy of a "once in a decade" nearby stripped-envelope supernova (SESN), SN 2023dbc, which, remarkably, has captured the emergence of dust precursors CO and SiO and allowed us to uniquely probe the poorly constrained ejecta composition of SESNe (DD-4436, PI: Shahbandeh). I will also discuss late-stage observations of SN 2004et and SN 2017eaw (GO-2666, PI: Fox), all four of which are nearby extragalactic Type IIP SNe. Our analysis of MIRI images of these two late-stage SNe reveals the highest SN dust mass observed since SN 1987A. SN 2004et is particularly notable, because its dust reservoirs rival those of SN 1987A, despite being significantly younger. These JWST observations have helped us constrain the geometry, origin, and heating mechanism of dust and support the theory that supernovae played a key role in supplying dust to the early Universe.

The attenuated emission model for the late-time JWST spectrum of SN2010jl

Oral Talk

Eli Dwek[1], **Ori Fox**[2]

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Abstract

We present a new model for the origin of the late-time IR emission from SN2010jl, detected by the JWST. In the conventional interpretation of its spectrum, the emission arises from various dust components characterized by different masses, temperatures, and locations. In this model, the attenuated ejecta emission model, the observed spectrum of SN2010jl is generated by the emission from hot newly-formed dust in the supernova ejecta that is absorbed by a layer of pre-existing or newly-formed silicate dust in the surrounding circumstellar medium. The model provides a very good fit to the silicate absorption features present in the spectrum, and provides strong constraints on the masses, temperatures, dust heating mechanisms, and the physical processes associated with the interaction of the SN with its surrounding CSM.

The Extinction Distances to Supernova Remnants and the dust properties

Invited Talk

Biwei Jiang

Beijing Normal University, China

Abstract

The distances to more than 60 supernova remnants are determined based on the assumption that the extinction increases sharply at the position of the SNR due to its high dust density. Afterwards, the extinction curves derived from the extinction in the optical-to-infrared bands are fitted by dust model. The results reveal that the silicate and carbonaceous dust experiences different changes in the SNR. Moreover, the dust mass of SNRs is estimated roughly, and its relation to the dust destruction in the SNRs will be discussed.

Dust destruction by the reverse shock in clumpy supernova remnants

Oral Talk

Florian Kirchschlager[1], Ilse De Looze[2], Nina Sartorio[2], Tassilo Scheffler[2], M. J. Barlow[3], Franziska Schmidt[3], and Felix Priestley[4]

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Abstract

Observations have proven that the expanding ejecta of supernova remnants (SNR) form up to 1 $M_\odot$ of dust in dense clumps of gas. Before the dust can be expelled into the interstellar medium and contribute to the interstellar dust budget, it has to survive the reverse shock that is generated through the interaction of the preceding supernova blast wave with the surrounding medium. However, both simulations and observations indicate that a significant amount of the newly formed dust can be destroyed by the reverse shock. Impinging gas particles evoke thermal and non-thermal sputtering of the dust grains but can also lead to grain growth by gas accretion. In addition, grain-grain collisions can result in shattering or vaporisation of one or both colliding grains and to a redistribution of the initial grain sizes. A number of previous studies have examined dust destruction rates caused by the passage of the reverse shock in SNRs. Their formalisms, approaches, and models vary widely, as do the resulting dust survival rates which span a range from 0 to 100 %. The different studies emphasize the strong dependence of the survival rate on dust and ejecta properties, but also on dust processes considered in the models. In order to draw more precise conclusions about the fate of dust in the ejecta, it is necessary to consider all relevant physical dust processes, to use a sophisticated model, and to know the dust and ejecta properties as well as possible. In this talk I will give an overview on the progress that has been made in the field of dust destruction in the ejecta of SNRs over the last five years. In particular, I will present results derived with our dust post-processing code Paperboats. Based on the output of highly resolved MHD simulations, we are able to calculate the dust dynamics, dust destruction and possible grain growth for dust material in a clump disrupted by the reverse shock. The modelling includes a multitude of dust processes which is unique in its number. Taking this into account, it was possible to improve the dust destruction determination in clumpy SNR ejecta and to calculate more accurate survival rates. Moreover, we are able to simulate dust density maps of the clump-shock interaction which allows the comparison with observations. I will outline the strong dependence of dust survival in SNRs on the dust grain sizes, clump density, magnetic field strength and orientation, as well as on the temporal evolution of the ejecta, in particular for the well-studied SNR Cassiopeia A.

Populating the Gap in Dust-Formation History of Type II(P) Supernovae with JWST

Oral Talk

Tamás Szalai

University of Szeged, Hungary

Abstract

Core-collapse supernovae (SNe), especially Type IIP ones, have long been considered to significantly contribute to the cosmic dust budget. Models of expanding ejecta predict $0.1-1\ M_\odot$ of dust in SNe IIP. New dust cools quickly and is therefore detectable at longer (mid-IR) wavelengths. However, only a handful of nearby SNe II(P) have shown direct observational evidence for dust condensation, and dust masses (based primarily on Spitzer data, generally limited to early epochs, and to >500 K temperatures) have been $2-3$ orders of magnitude smaller than theoretical predictions. At the same time, far-IR/submm observations of Galactic SN remnants (SNRs) and the very nearby (~ 50 kpc) SN 1987A have revealed that massive cooler dust reservoirs may form over years or decades in SNe. As demonstrated recently, James Webb Space Telescope (JWST) finally allows to reveal hidden cool ($\sim 100-200$ K) dust reservoirs in a larger sample of extragalactic SNe and help to fill the currently existing gap in the dust-formation history of Type II(P) SNe. Here we give a summary on the results of our JWST GO Cycle-1 2666 program, and also a taste of our other ongoing JWST projects looking for dust in SNe.

Modeling dust formation in supernovae

Oral Talk

Arkaprabha Sarangi

DARK, Niels Bohr Institute, University of Copenhagen, Denmark

Abstract

Cosmic dust plays a vital role in shaping the evolution and spectral characteristics of galaxies. Core-collapse supernovae are recognized as significant contributors to dust formation in both local and high-redshift galaxies. Supernova environments are characterized by exotic phenomena such as shocks, radioactivity, non-equilibrium chemical processes, and rapid cooling. In my presentation, I will provide an overview of the current state-of-the-art in modeling dust formation in supernovae, drawing on the physics and chemistry of these environments. I will discuss the nature and mechanisms of dust production in (a) the pre-supernova progenitor, (b) the ejecta post-explosion, and (c) the interaction region of the forward shock and the circumstellar medium (CSM). This talk will address all the features observed in last two years with JWST, as well as Spitzer observations of supernovae over the past few decades.

The Effects of Escaping Cosmic Rays From Supernova Remnants in The Interstellar Medium

Oral Talk

Jiro Shimoda

Institute for Cosmic Ray Research, The University of Tokyo, Japan

Abstract

We study the effects of cosmic rays (CRs) escaping from supernova remnants (SNRs), which have not been studied in detail. When the CRs are scattered by Alfvén waves, their linear momentum is transferred to the waves. The waves are finally dissipated and heating the interstellar medium (ISM). The heating rate is given by a product of the Alfvén speed and the CR pressure gradient. Thus, the heating effects of escaping CRs reflect the total amount of accelerated CRs at the shock (injection rate) and the extent of CR "halo" around the SNR (diffusion coefficient). We find that the heating effect can be significant for the ISM with a density of $\sim 10^{-3} - 10^{-2}$ cm^{-3} at the late Sedov stage (the age is $\sim 10^4$ yr). The temperature of the heated gas can be $\sim$ keV, which is larger than the virial temperature of our galaxy (~ 0.3 keV). Thus, the heating effects can result in the outflow from the Galactic disk, which is one of the important feedback processes for galactic evolution. We will review our results and discuss how to test the heating effects by observations.

Session 6.

SN/SNR dust, environments, feedback – Posters

C I/CO abundance ratio of shock-excited gas in the Magellanic Supernova Remnant N63A

Poster

Natsuko Izumi[1,2], Hidetoshi Sano[1], Kenji Furuya[2], Nanase Harada[2], Kazuki Tokuda[3], and Mitsuyoshi Yamagishi[4]

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Abstract

Atomic carbon line emission (C I) is considered a reliable tracer for inferring the distribution of H_2 in galaxies, comparable to low-J CO line emission. However, the modification of the C I/CO abundance ratio under environments where cosmic-ray-induced and/or shock-induced destruction of CO molecules occurs efficiently is not fully understood. Therefore, we conducted high-resolution and sensitivity observations of [C I] and CO line emissions toward the pre- and post-shocked molecular clouds in the Magellanic supernova remnant (SNR) N63A using ALMA. N63A offers C I/CO abundance ratios through cosmic-ray and shock-induced destructions of CO, free from contamination along the line of sight. As a result, we found a correlation between the C I/CO abundance ratio and CO intensity in these clouds, suggesting the dominance of ultraviolet (UV) radiation in influencing the ratio across all clouds. We also found that the C I/CO abundance ratio in pre-shocked molecular clouds exhibited a wider scatter compared to that in the post-shocked regions, possibly suggesting the environmental factors (e.g., cosmic ray abundance, supernova shocks). In this poster, we will discuss the environmental factors as a function of the C I/CO abundance ratio.

Dust destruction in the clumpy remnant Cassiopeia A: Impact of inhomogeneous dust distributions

Poster

Maxim Reckelbus[1], Florian Kirchschlager[1], Nina Sartorio[1], Ilse De Looze[1], Tassilo Scheffler[1]

[1]Ghent University, Belgium

Abstract

Dense clumps in remnants of supernova explosions offer ideal conditions for the formation of dust grains, and observations have proven the presence of dust material around a few tens of supernova remnants (SNRs). However, the SNRs are also pervaded by high-energy shock waves which can destroy a significant amount of the freshly produced dust material. To estimate the net dust contribution per supernova, it is important to study the amount of surviving dust. Our simulations of dust destruction in SNRs focus on the cloud-crushing scenario in which a single clump of gas and dust is impacted by a planar shock wave. This setup has the advantage of being able to investigate the destruction of the dense clump at high spatial resolution. The dust survival rate in this clump strongly depends on the surrounding gas conditions and on the properties of the clump. So far, most of the numerical models consider only spherical, homogeneous clumps without any internal structure or spatial variations. However, recent JWST observations have shown that clumps in the SNR Cassiopeia A (Cas A) can not be expected to be homogeneous and spherical. In particular, the dust mass distribution can depend on the location within the clump. Moreover, it is conceivable that the grain size distribution in the clump is manifold and inhomogeneous, with larger grain sizes in the inner parts and smaller grains at the outer edges of the clump. The inhomogeneous dust mass distribution and the spatial distribution of the grain sizes will have a significant impact on the dust survival rate, though it is an open question to which degree. To study the dust destruction in a shock-disrupted clump of gas, we model the cloud-crushing problem using the MHD code AstroBEAR. We post-process our hydrodynamical simulations with the dust physics code Paperboats. In the dust post-processing, the dust material is transported due to collisional drag, plasma drag and Lorentz forces. The dust destruction processes include thermal and non-thermal sputtering, fragmentation and vaporisation, and cause a redistribution of the initial grain sizes. The inhomogeneous dust mass distribution is realised by introducing a radially varying dust-to-gas mass ratio; the spatial variation of the dust grain sizes is modelled with a distribution of small grains outside and a second distribution of large grains inside a critical radius from the clump center. We will show the impact of an inhomogeneous distribution of dust mass and grain size on the total dust survival rate and on the final dust density maps of the shocked clumps.

The impact of CSM properties on the dust destruction by supernovae forward shocks

Poster

Nina Sanches Sartorio[1], Ilse De Looze, Florian Kirchschlager, Mike Barlow, Franziska Schmidt

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Abstract

Despite extensive investigation, the impact of supernovae on the dust budget remains an unresolved issue in astrophysics. Detection of newly formed dust grains in the ejecta of young supernova remnants, such as SN 1987A and Cas A, highlights their potential to condense up to one solar mass of dust in a short period. Core-collapse supernovae have thus emerged as significant sources of interstellar dust, not only locally but also in the high-redshift Universe. However, the extent to which supernova dust contributes to the interstellar medium remains unclear. While attention has focused on the role of the reverse shock in dust destruction, the forward shock alone is anticipated to annihilate substantial quantities of dust within the circumstellar medium. Numerical simulations project that a supernova forward shock could sweep up several thousand solar masses, endangering tens of solar masses of dust grains to sputtering and shattering processes. If a single supernova destroys more than a few solar masses, it could be classified definitively as a dust sink rather than a dust producer. Thus, a deeper understanding of forward shock-induced dust destruction is imperative to assess supernovae's impact on the dust budget. This presentation elucidates the critical influence of environmental heterogeneity on the forward shock's efficacy in dust destruction. Through 3D simulations of forward shock expansion across diverse circumstellar medium environments characterized by varying turbulence levels, pre-shock gas temperatures, and densities, we demonstrate how minor changes to these parameters can lead to substantial variations in dust destruction, often by an order of magnitude. These findings can shift the balance, once again positioning supernovae as potential dust producers.

ALMA Observations of Supernova Remnant N49 in the Large Magellanic Cloud. II. Non-LTE Analysis of Shock-heated Molecular Clouds

Poster

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Abstract

We present the first compelling evidence of shock-heated molecular clouds associated with the supernova remnant (SNR) N49 in the Large Magellanic Cloud (LMC). Using ^{12}CO(J = 2-1, 3-2) and ^{13}CO(J = 2-1) line emission data taken with the Atacama Large Millimeter/Submillimeter Array, we derived the H_2 number density and kinetic temperature of eight ^{13}CO-detected clouds using the large velocity gradient approximation at a resolution of 3.5 arcsec ($\sim$0.8 pc at the LMC distance). The physical properties of the clouds are divided into two categories: three of them near the shock front show the highest temperatures of $\sim$50 K with densities of $\sim$500-700 cm^{-3}, while other clouds slightly distant from the SNR have moderate temperatures of 20 K with densities of $\sim$800-1300 cm^{-3}. The former clouds were heated by supernova shocks, but the latter were dominantly affected by the cosmic-ray heating. These findings are consistent with the efficient production of X-ray recombining plasma in N49 due to thermal conduction between the cold clouds and hot plasma. We also find that the gas pressure is roughly constant except for the three shock-engulfed clouds inside or on the SNR shell, suggesting that almost no clouds have evaporated within the short SNR age of $\sim$4800 yr. This result is compatible with the shock-interaction model with dense and clumpy clouds inside a low-density wind bubble.

Dust destruction by supernova remnant forward shocks in a turbulent interstellar medium

Poster

Tassilo Scheffler, Nina Sanches Sartorio, Florian Kirchschlager and Ilse De Looze

University of Ghent, Belgium

Abstract

Core-collapse supernovae are one of the main producers of cosmic dust. Their remnants incorporate the perfect conditions for molecules to grow to dust grains, starting from a few hundred days after the explosion. However, the produced 0.01 to 1 solar masses of dust per supernova will eventually encounter the energetic reverse shock, while an even larger amount of pre-existing interstellar dust is at risk of destruction by the forward shock. Numerical studies estimate that the total dust destruction of the forward shock ranges somewhere between 0.3 to 70 solar masses, possibly turning supernovae into dust sinks rather than dust sources. In the last decades, the importance of constraining the dust destruction rate of supernova remnant shocks has become even more pressing since other dust sources such as asymptotic giant branch stars alone cannot explain observations of dusty galaxies at high redshift. To realistically study the destroyed interstellar dust mass of forward shocks, we perform new high-resolution 3D supernova remnant simulations with AREPO and the dust post-processing code PAPERBOATS, which includes various dust transport and destruction processes. Unlike previous studies, we consider several complex phenomena simultaneously: sputtering, grain-grain collisions, magnetic fields, and a turbulent surrounding interstellar medium. Especially the inhomogeneous medium is of great importance, as it can lead to significant dust shielding in high-density filaments. Previous work has mostly driven the turbulence by exploding multiple supernovae, lacking the observed small-scale filaments that can strongly influence the evolution of the supernova remnant. We drive the inhomogeneities by inserting Fourier waves randomly at different scales and locations into our simulation box using an Ornstein-Uhlenbeck process. After their interaction, all scales of turbulence down to the Jeans length can be included and the system most closely resembles observations of the inhomogeneous interstellar medium. The supernova, which is then induced into the system, develops highly asymmetric forward and reverse shocks, similar to observations of young supernova remnants such as Cassiopeia A. By covering a wide parameter space of different dust grain species, interstellar medium densities, temperatures, and magnetic field strengths, we are able to constrain the actual amount of dust destroyed by the forward shock, depending on the properties of the supernova explosion site.

Constraining the progenitor properties of the Type Ib supernova iPTF13bvn through its environment with HST and MUSE

Poster

Adam Singleton[1] and J. R. Maund[2]

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Abstract

The relationship between a massive star's evolution and the resultant supernova classification at the end of its life is an incomplete picture, and has mostly relied on high quality pre/post-explosion data for a limited number of nearby supernovae. To remedy this, we are combining archival photometric data with integral field unit (IFU) spectroscopic data to spatially resolve the stars, gas and dust in the environments of core-collapse supernovae (SNe). The aim of this project is to expand the number of well constrained SN progenitors that produce the full variety of SN classifications we observe. In order to build this new approach to environmental analysis, we started with the Type Ib SN iPTF13bvn in NGC 5806. New estimates for the progenitor age, mass and extinction were found using a Bayesian hierarchical mixture model of the stellar population surrounding iPTF13bvn, using Hubble Space Telescope UV and optical imaging filters. The structure, properties and dynamics of the gas and dust in the environment of iPTF13bvn were explored using IFU spectroscopic data from the Very Large Telescope (VLT/MUSE). Within the environment of iPTF13bvn, we resolved two stellar populations with unique age (τ=log[t years]) and extinction (A_V) values: $\tau_1 = 6.59^{+0.04}_{-0.05}$, $A_{V,1} = 0.95^{+0.07}_{-0.06}$ mag and $\tau_2 = 6.97^{+0.06}_{-0.06}$, $A_{V,2} = 0.53^{+0.10}_{-0.08}$ mag. Despite the small errors produced by our Bayesian approach, these values agree within 3σ to the age found in Sun et al. (2023) and extinction found in Maund (2018) for iPTF13bvn. Our IFU spectroscopic analysis finds a spread of extinction values that could imply an underestimation in extinction purely from the stellar analysis, as well as assisting in building a 3D picture of the environment within the spiral arm of NGC 5806. The results from this study show that the complex relationship between stars, gas and dust can be used, through the combination of HST imaging and high spatial resolution integral field spectroscopy, to resolve degeneracies that have plagued previous studies of the environments of supernovae. I will discuss the application of this approach to a broader catalogue of local supernovae and the implications for understanding the progenitors of supernovae (especially in the absence of fortuitous pre-explosion imaging).

Time-dependent feedback of core-collapse supernovae from binary progenitors via detailed binary population synthesis models

Poster

Dimitris Souropanis[1], **Manos Zapartas**[1], **and Tassos Fragos**[2]

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Abstract

Core-collapse supernovae (CCSNe) represent energetic events marking the end of the evolution of massive stars. Feedback from these supernovae is a critical factor in the chemical evolution and overall evolution of galaxies, as the injection of energy, momentum and metals into the surrounding medium regulate the rate and efficiency of star formation within galaxies, drive outflows and turbulence in the interstellar medium and disperse metals synthesized in stars. However, key questions persist regarding the types of stars undergoing CCSNe events, their timing, and the amount of energy, momentum, and mass they release. Given that most massive stars are born in binary star systems, binary interactions can drastically alter the evolution of massive supernovae progenitors and their feedback to the environment. Zapartas et al. (2017) studied the core-collapse supernova rate as a function of time taking into account binary interactions, using simple parametric population synthesis models. To understand better the mechanical and energetic feedback from supernovae, we conducted a population synthesis study using the next-generation, state-of-the-art POSYDON binary population synthesis code, based on the much higher accuracy of detailed MESA binary models, taking into account effects such as tides, stripping during mass transfer, mass accretion and merging (in a simplified way), for different metallicities and inferring the outcome of core-collapse using different SN explodability prescriptions. This talk seeks to present the effects of binary interactions of massive stellar progenitors on the observed supernova type, mass ejected, momentum, and energy from supernovae as a function of time.

A Yebes W band Line Survey towards an Unshocked Molecular Cloud of Supernova Remnant 3C391: Evidence of Cosmic-Ray-Induced Chemistry

Poster

Tianyu Tu

Nanjing University, China

Abstract

Cosmic rays (CRs) have strong influences on the chemistry of dense molecular clouds (MCs). To study the detailed chemistry induced by CRs, we conducted a Yebes W band line survey towards an unshocked MC (which we named as 3C391:NML) associated with supernova remnant (SNR) 3C391. We detected emission lines of 18 molecular species in total and estimated their column densities with local thermodynatic equilibrium (LTE) and non-LTE analysis. Using the abundance ratio $N(\mathrm{HCO^+})/N(\mathrm{CO})$ and an upper limit of $N(\mathrm{DCO^+})/N(\mathrm{HCO^+})$, we estimated the CR ionization rate of 3C391:NML is $\zeta \gtrsim 2.7\times\ 10^{-14}\mathrm{s}^{-1}$. However, we caution on adopting this value because chemical equilibrium, which is a prerequisite of using the equations, is not necessarily reached in 3C391:NML. We observed lower $N(\mathrm{HOC^+})/N(\mathrm{HCO^+})$, higher $N(\mathrm{HCS^+})/N(\mathrm{CS})$, and higher $X(\text{-}\mathrm{C_3H^+})$ by an order of magnitude in 3C391:NML compared with typical values in quiescent dense MCs. We found that enhanced CR ionization rate ($\sim 10^{-16}$ or $\sim 10^{-14}$ s^{-1}) is preferred to reproduce the observation with chemical model. But a more robust estimation of the temperature from observation is crucial to the estimation of CR ionization rate in 3C391:NML.

The slow formation of dust by core collapse supernovae

Poster

Roger Wesson

Cardiff University, UK

Abstract

Numerous core collapse supernovae (CCSNe) have now been shown to have formed significant quantities (>0.1 $M_\odot$) of dust. This implies a very high efficiency for the condensation of refractory elements into grains in the supernova ejecta, and indicates that CCSNe can form enough dust to account for observations of high-redshift quasars which have become extremely dusty within a few hundred million years of the Big Bang. However, while theories of dust formation predict that it should be complete within a few hundred days of the supernova explosion, observations suggest that dust formation continues for several thousand days. Using spectral energy distribution (SED) fitting alone, it can be difficult or impossible to determine whether infrared emission is from newly formed dust or from pre-existing dust flash-heated by the supernova. Optical emission line profiles, on the other hand, are affected by dust with an expanding emission region but not by dust external to it. I will present recent results using both SED fitting and emission line profiles to study the dust formation history of SN 1995N, showing that emission previously attributed to a thermal echo is in fact due to newly formed dust in the ejecta, which must have mostly formed many years after the explosion. A compilation of all available literature supernova dust masses strongly supports the picture of dust forming over decades, in sharp contrast to theoretical predictions.

Not gone with the wind: survival of high-velocity molecular clouds in the Galactic Centre

Poster

Mengfei Zhang and Li Miao

Zhejiang University, China

Abstract

The high-velocity atomic clouds in the Galactic center were observed many years ago and can be explained as the acceleration from the activity of supermassive black hole or starburst. However, the high-velocity molecular clouds (HVMCs) discovered recently are denser and cooler than atomic clouds and are more difficult to be accelerated to high velocity without disruption. To study the possible mechanisms behind the formation of HVMCs and their connection to feedback processes, a series of simulations for a starburst model are performed and further examined. The simulations show a subsequent random supernovae explosions about millions years ago in the central molecular zone (CMZ) can accelerate HVMCs to high velocity and survive until it reaches 1 kpc above the Galactic plane, well consistent with the observation, which implies the potential influence of star activity on the Galactic feedback is considerable.

A molecular line survey toward clumps G and E in supernova remnant IC 443 with the Submillimeter Array

Poster

Qianqian Zhang[1], Yang Chen[1], Lingrui Lin[1], Zhiyu Zhang[1], Ping Zhou[1]

[1] Nanjing University, China

Abstract

Investigations into molecular clouds interacting with supernova remnants (SNRs) can shed light on the influences of SNR shock waves on the interstellar medium. To understand how the SNRs alter the physical and chemical properties of molecular gases in detail, we performed a line survey toward clumps G and E in SNR IC 443 at 1.3 mm with the Submillimeter Array. Emissions of CO, HCO^+, HCN, CN, H_2CO, CS, SO and SiO are detected. The CO data are combined with the IRAM 30m data. In the high-resolution images, we discern several structures that are not resolved in the single dish observations. Some of these structures are spatially coincident with the mid-infrared emission. Different molecular species show different intensity distributions in clump G, which is possibly due to their chemical properties. The line profiles and the position-velocity diagrams of both clumps indicate the existence of multiple shocks propagating in the medium with different densities. We derive a H_2 volume density of $\sim 10^6$ cm^{-3} and a kinetic temperature higher than 50 K for clump G from the SiO and SO transitions. The column densities of different species differ from previous results by less than an order of magnitude.

Estimation of the Dust Mass with Infrared Emission and Extinction of the Supernova Remnants: G156.2+5.7, G109.1-1.0, G166.0+4.3, G93.7-0.2

Poster

Zhe Zhang[1], Biwei Jiang[1], Jun Li[2], and He Zhao[3]

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[2]Guangzhou University, China
[3]Purple Mountain Observatory, China

Abstract

The dust mass is estimated from the infrared emission and visual extinction of four supernova remnants (SNRs), specifically G156.2+5.7, G109.1−1.0, G166.0+4.3 and G93.7−0.2. The spectral energy distribution (SED) of the dust consists of the photometric fluxes from the WISE, IRAS, AKARI, and Planck space telescopes, covering the wavelength range from about 10 microns to 1mm. After subtracting the synchrotron radiation and considering the spectral line emission, the dust mass is calculated by fitting the SED with a warm plus cold dust component model assuming a composition of silicate and amorphous carbon. The resultant temperature and mass of the warm component and of the cold component are 64 K and 0.002 $M_\odot$, $\sim$13 K and 151.9 $M_\odot$, respectively for G156.2+5.7; $\sim$ 60 K and 0.04 $M_\odot$, $\sim$16 K and 100.6 $M_\odot$ for G109.1−1.0; $\sim$44 K and 0.05 $M_\odot$, $\sim$13 K and 76.8 $M_\odot$ for G166.0+4.3; $\sim$75 K and 0.008 $M_\odot$, $\sim$14 K and 481.4 $M_\odot$ for G93.7−0.2. On the other hand, the variation of the interstellar extinction based on the 3D extinction map along the sightline towards the SNR is used to determine the distance to the object and the extinction by the SNR is used to estimate the dust mass. The dust mass derived from the extinction is 117.9 $M_\odot$ for G156.2+5.7, 108.8 $M_\odot$ for G109.1−1.0, 93.7 $M_\odot$ for G166.0+4.3, and 123.7 $M_\odot$ for G93.7−0.2. The comparison and implication of these estimations are discussed.

Disentangling possible dust components of core-collapse supernovae within a Bayesian framework

Poster

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Abstract

Core-collapse supernovae (CCSNe) have long been considered one of the essential stellar sources of dust, as they could explain the observed dust content of high-redshift galaxies and a crucial part of the cosmic dust content of the Universe. However, only a small number of young extragalactic SNe show direct observational evidence for dust condensation, and several questions remain unanswered regarding the dust parameters and their sources. Dust grains in the environment of CCSNe could be either newly formed or pre-existing and heated due to the SN explosion. The dust components could be traced by modeling both the emerging infrared (IR) excess and the red-blue asymmetries in optical and near-IR emission-line profiles of SNe. By applying both modeling approaches simultaneously, it is possible to determine the grain properties and the location of dust formation and, therefore, successfully disentangle possible pre-existing and newly formed SN dust components. First, we investigate the mid-IR emission of CCSNe by fitting analytical dust models to the spectral energy distributions to provide a foundation for the advanced models. However, to accurately describe the gas and dust material in the environment of CCSNe, we need to follow the possible light-matter interactions. Thus, we compute numerical dust models with MOCASSIN. We interpret our models within a Bayesian data inference framework linked to an MCMC method, allowing us to explore the parameter space of complex models efficiently and describe the relationship of given parameters. With this comprehensive method, we could characterize the posterior probability distribution of the model parameters. Moreover, we model the optical line emission of CCSNe with DAMOCLES to constrain the possible location of dust grains in SN ejecta and the properties of SN dust. By combining these models, we could use consistent morphologies for dust, gas, and heating sources. Finally, in the era of *JWST*, statistical methods could play a significant role in the efficient and systematic investigation of CCSNe. Its extended and outstanding quality datasets provide an opportunity to exploit the advantages of the Bayesian framework. We aim to analyze different types and ages of CCSNe using a consistent methodology based on the most precious measurements available to date, including data from *JWST*. Moreover, it will enable us to constrain the timing of dust formation for a statistical sample of SNe.

Session 7.

PWN Diversity; Structures, Bowshocks and Magnetar Wind Nebulae – Oral Talks

A Radio Eye on Pulsar Wind Nebulae

Invited Talk

Ronald Kothes

National Research Council Canada

Abstract

Fast rotating neutron stars produce a steady energetic wind of relativistic particles and magnetic fields. This pulsar wind is released into the expanding ejecta of a core collapse supernova explosion, creating a synchrotron emitting nebula observable from radio to gamma-rays. In the radio band, smooth, highly linearly polarized continuum emission arises from well-ordered magnetic fields, carrying information on the internal magnetic field configuration of the nebula and the particle acceleration mechanism of the pulsar. In this review, I will summarize recent advances in the field from a radio astronomer's point of view. In particular, I will focus on the development of radio polarization emission characteristics and the magnetic field structure with respect to the different phases of PWN evolution.

The Crab Nebula at 150 MHz and sub-arcsecond resolution with the LOFAR Long Baselines

Oral Talk

Maria Arias

Leiden Observatory, The Netherlands

Abstract

The Crab Nebula, the pulsar wind nebula surrounding the Crab pulsar, is one of the most thoroughly studied objects in the sky, and it might appear unlikely that, at this stage, radio observations could shed new light on its properties. In this talk, I will present a subarcsecond resolution image of the nebula at 150 MHz, possibly the highest dynamic range image ever made with LOFAR. The new observations allow us to measure the expansion of the pulsar wind nebula, which resulted from a supernova explosion in 1054. More interestingly, our map shows new absorption features in a filament southwest of the pulsar, including knots with a spectral index of approximately 3 (for $S_\nu \propto \nu^\alpha$). I will discuss free-free absorption and synchrotron self-absorption as the possible origins for the observed absorption features, and their implications for the physical conditions in the knots.

Pulsar Wind Nebulae in X-rays: Population Properties, Outstanding Results, and Open Questions

Invited Talk

Oleg Kargaltsev[1], George Pavlov[2], Seth Gagnon[1], Noel Klingler[3,4]

[1]The George Washington University, USA
[2]Pennsylvania State University, USA
[3]NASA GSFC, USA
[4]University of Maryland, USA

Abstract

Observations with the Chandra X-ray Observatory have led to remarkable progress in our understanding of pulsar winds and pulsar wind nebulae (PWNe). Deep, high-resolution imaging in X-rays revealed the fine structure of pulsar winds, such as termination shocks in the equatorial wind, polar jets with moving knots, cometary-shaped bow shocks, and puzzling misaligned outflows. Spatially-resolved X-ray spectroscopy has enabled measurements of the particle injection spectrum in the vicinity of the termination shock and investigation of the spectral evolution as a function of distance from the pulsar. Repeated observations have also demonstrated that the PWNe can be highly variable on various timescales. In my talk I will review the most significant recent results, provide an overview of properties of the entire X-ray PWN population, and discuss the connection between the pulsar and PWN properties.

Discovery of Bow-Shock Pulsar Wind Nebulae in New Generation Radio Continuum Surveys

Oral Talk

Sanja Lazarevic[1,2], D. Filipovic Miroslav[1], Shi Dai[2], Chandreyee Maitra[3], Roland Kothes, Philip Edwards[2]

[1]Western Sydney University, Australia
[2]CSIRO Space and Astronomy, Australia
[3]IMPRS, Germany

Abstract

Pulsars and their Wind Nebulae exhibit intriguing features when moving at supersonic speeds through ambient medium such as bow-shaped shocks and cometary tails. Studying the PWNe provides valuable insights into pulsars, radiative efficiency, properties of the surrounding medium, and the physics of the wind-medium interaction. Additionally, it contributes to our understanding of the distribution of the natal kick velocities that neutron stars acquire during supernova implosions. The first report of this phenomenon dates to 1987, and prior to the Chandra X-ray Observatory's launch in 1999, only a handful of the PWNe had been identified. Chandra's enhanced capabilities have led to the identification of approximately 30 pulsars displaying signs of supersonic motion. However, recent advancements in radio-continuum surveys obtained with ASKAP and MeerKAT have transformed the rarity of these objects. In this presentation, I will summarise the discovery and analysis of Potoroo, a remarkable bow-shock PWN with one of the longest radio tails, detected in the EMU pilot survey. The latter part of the talk will highlight the six best new examples of the class, showcasing a diverse range of morphologies. All discoveries have been made in the Galactic Plane fields of the EMU main survey, with promising prospects for more to come.

Structure of the Pulsar Wind Nebula in SNR 0540-69.3 Revealed by ALMA

Oral Talk

Po-Sheng Ou[1], Chu You-Hua[2]

[1]ASIAA/NTU
[2]ASIAA/NSYSU

Abstract

0540-69.3 is the second youngest supernova remnant (SNR) in the Large Magellanic Cloud (LMC). It is called the "twin" of the Crab Nebula due to the similarities in their pulsar wind nebulas (PWNe) and ages; however, 0540-69.3 is likely located within a more complex environment and originated from a more massive progenitor star. In this talk, I will present our ALMA images of the central region of SNR 0540-69.3 that reveal detailed structures of the PWN. These structures are compared to the Crab and SN 1987A to understand the effect of progenitor mass, environment, and evolution on the central regions of SNRs. Based on the comparisons between our ALMA images and multiwavelength observations, we propose a possible scenario for 0540-69.3 with interactions between the PWN, SN ejecta, and circumstellar medium (CSM). Furthermore, we use the Herschel and ALMA data to show the evidence of cold dust production at the center of SNR 0540-69.3, and discuss SN ejecta dust associated with PWNe.

Spatial Variations and Breaks in the Optical-NIR spectra of the Pulsar and PWN in SNR 0540-69.3

Oral Talk

Linda Tenhu, J. Larsson, J. Sollerman, P. Lundqvist, J. Spyromilio, J. D. Lyman, and G. Olofsson

KTH Royal Institute of Technology, Sweden

Abstract

The supernova remnant SNR 0540-69.3, twin of the Crab Nebula, offers an excellent opportunity to study the continuum emission from a young pulsar and pulsar-wind nebula (PWN). We present observations taken with the VLT instruments MUSE and X-shooter in the wavelength range 3000–25,000 Å, which allow us to study spatial variations of the optical spectra, along with the first near-infrared (NIR) spectrum of the source. We model the optical spectra with a power law (PL) $F_\nu \propto \nu^{-\alpha}$) and find clear spatial variations (including a torus-jet structure) in the spectral index across the PWN. Generally, we find spectral hardening toward the outer parts, from $\alpha \sim 1.1$ to ~ 0.1, which may indicate particle reacceleration by the PWN shock at the inner edge of the ejecta or alternatively time variability of the pulsar wind. The optical-NIR spectrum of the PWN is best described by a broken PL, confirming that several breaks are needed to model the full spectral energy distribution of the PWN, suggesting the presence of more than one particle population. Finally, subtracting the PWN contribution from the pulsar spectrum we find that the spectrum is best described with a broken-PL model with a flat and a positive spectral index, in contrast to the Crab pulsar that has a negative spectral index and no break in the optical. This might imply that differences in the pulsars propagate to the PWN spectra.

Session 7.

PWN Diversity; Structures, Bowshocks and Magnetar Wind Nebulae – Posters

Cosmic Ray Leptons Escaping from CTA 1?

Poster

Jason Alford, Joseph Gelfand, Eric Gotthelf, Kaya Mori, Pat Slane

NYU Abu Dhabi, United Arab Emirates

Abstract

Many Galactic TeV sources are associated with middle-aged ($\sim 10^{4-5}$) pulsar wind nebulae (PWNe), with the γ-ray emission extending beyond the X-rays. This suggests that high-energy $e^{\pm}$ first escape from the PWN, and then produce the γ-rays through inverse Compton (IC) scattering. However, how they escape from the PWN is poorly understood, in part because there are very few examples of systems where the particles are 'caught in the act' of escaping from the PWN. Understanding this process requires spatially-resolved measurements of the diffuse, X-ray spectrum of the extended TeV source. Spatially resolved spectral measurements of the PWN in CTA 1 are suggestive of high-energy $e^{\pm}$ 'caught in the act' of escaping from the PWN. We have analyzed a new 150 ks NuSTAR observation of the PWN in CTA 1, as well as an archival 120 ks XMM observation, and will present initial results from our analyses.

"Mirage" and large offsets in the data as a result of asymmetric cosmic ray diffusion

Poster

Yiwei Bao, Yang Chen, Gwenael Giacinti, Ruo-yu Liu, and Hai-ming Zhang

Nanjing University, China

Abstract

We show that a large asymmetric halo may be misidentified as multiple "mirage" sources, and that asymmetric diffusion could lead to a very large offset between the injection site and the identified halo. We add background noise into the region and try to identify the sources. We utilize the concept of asymmetric diffusion to elucidate several observed sources that were previously challenging to interpret. Our model offers intuitive explanations for these observations and has the potential to help identify a broad range of sources in the future.

Using CFHT's SITELLE to probe the long-sought shell in the Crab nebula

Poster

Lucas Victor da Conceição[1], Janette Suherli[1], Samar Safi-Harb[1], Ivo Seitenzahl[2] and Ashley Ruiter[2]

[1]University of Manitoba, Canada
[2]Australian National University, Australia

Abstract

Supernova remnants and their associated pulsars have long fascinated astronomers. However, a persistent enigma remains; the absence of a supernova shell around certain young pulsar wind nebulae. Perhaps, the most famous example is the Crab Nebula, which after a decades-long search for its supernova shell with standard techniques in radio and X-rays is still "shell-less", a long-standing puzzle in Supernova Remnant astrophysics. In this study, we address this question by employing the SITELLE instrument from the CFHT Canada-France-Hawaii-Telescope (CFHT) equipped with a large field of view and high-resolution spectroscopy of key emission lines. In particular, we aim to survey a large region around the visible nebula using the coronal emission line [Fe XIV] 5303 as a diagnostic for the search for the forward shock. Our methodology consists of integral field unit (IFU) spectroscopy with imagery to construct detailed flux and velocity maps of the [Fe XIV] line outside of the visible nebula. Leveraging the emission modelling capabilities of the astrophysical code "MAPPINGS V", we aim to discern the intricate interplay of physical processes within and outside the nebula. Our primary objective is to derive plasma temperature estimates and evaluate whether the observed emission properties align with theoretical predictions for the forward shock. By combining observational data with advanced modelling techniques, we aim to shed light on the long-standing puzzle around the missing shell in this iconic pulsar wind nebula.

Chandra X-ray Observations of PSR J1849–0001 and its Pulsar Wind Nebula

Poster

Seth Gagnon[1], Oleg Kargaltsev[1], Noel Klinger[2]

[1]The George Washington University, USA
[2]NASA GSFC, UMBC, USA

Abstract

The Chandra X-ray Observatory (CXO) observed PSR J1849-0001 and its PWN, coincident with the TeV source HESS J1849-000, for 108-KS. Our analysis of the new and old (archival) CO data allowed for resolution of the pulsar from the PWN, exploration of the PWN morphology on arcsecond and arcminute scales, and spectral analysis of different regions of the PWN. Both the pulsar and the compact inner PWN spectra are hard with power-law photon indices of 1.20 ± 0.07 and 1.36 ± 0.14 respectively. The jet-dominated PWN with a relatively low luminosity, lack of γ-ray pulsations, relatively hard and non-thermal spectrum of the pulsar, and its sine-like pulse profile, indicate a relatively small angle between the pulsar's spin and magnetic dipole axis. In this respect, it shares similar properties with a few other so-called MeV pulsars. Single-zone modeling can roughly describe the joint X-ray and TeV SED, although the obtained magnetic field value is unrealistically low. A more realistic scenario is the presence of a relic PWN, no longer emitting synchrotron X-rays but still radiating in TeV via inverse-Compton upscattering. We also serendipitously detected surprisingly bright X-ray emission from a very wide binary whose components should not be interacting.

An Exploration of Misaligned Outflows in Pulsar Wind Nebulae

Poster

Xianghua Li

Yunnan University, China

Abstract

This review offers an introductory exploration of misaligned outflows in pulsar wind nebulae (PWNe), a phenomenon where the outflows are not aligned with a reference direction, such as the pulsar's velocity vector. These misalignments, observed in several PWNe, provide insights into the nebulae's morphology and evolution. The review covers the observed properties of these outflows, the methods of observation, and the theoretical models proposed for their explanation. It concludes by acknowledging the areas that need further research, emphasizing the importance of continued study in this intriguing area of astrophysics.

Diagnosis of Pulsar Wind Nebula dynamics using their filamentary structure

Poster

Soham Mandal[1], Paul Duffell[1], Abigail Polin[2], and Dan Milisavljevic[1]

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[2]Caltech, USA

Abstract

The web of filaments in pulsar wind nebulae (PWNe) such as the Crab are believed to be due to turbulence from the interaction of the pulsar wind with the stellar ejecta. In this work, we develop 3D hydrodynamical models to study this turbulent activity and signatures that the stellar structure and the wind dynamics impart upon it. We study the evolution of the power spectrum of our hydro models as the wind expands against a shallow density profile inner ejecta (self-similar stage) and eventually blows out (non self-similarly) into a low density outer ejecta. We also examine the effects of spindown of the central pulsar, an aspherical (equatorial) wind, and jets. The power spectrum of the self-similar models is found to be a broken power-law, with the specific shape decided by the density profile of the inner ejecta. The shape of the power spectrum at large wavenumbers is too steep to be consistent with a turbulent cascade, as also found for supernova remnants without a central compact object. Both the pulsar spindown and blowout into thinner outer ejecta are found to leave distinctly identifiable signatures in the power spectrum of PWNe. We also perform power spectral analysis with three-dimensional reconstruction of the Crab nebula and compare to our models. The filaments in the Crab indicate that the wind is still confined by a shallow inner ejecta with a density profile $\rho \propto r^{-1}$, and that the pulsar has spun down considerably, allowing the long filaments extending to its center to survive the turbulent mixing.

Pulsar halos as an origin of the Galactic diffuse TeV–PeV emission: Insight from LHAASO and IceCube

Poster

Kai Yan

Nanjing University, China

Abstract

The high-energy diffuse gamma-ray emission and neutrino emission are expected from the Galactic plane, generated by hadronuclear interactions between cosmic rays (CR) and the interstellar medium (ISM). Therefore, measurements of these diffuse emission will provide important clues on the origin and nature of Galactic CRs. Comparing the latest observations of LHAASO and IceCube on the diffuse Galactic gamma-ray and neutrino emission respectively, we suggest that the diffuse gamma-ray emission at multi-TeV energies contains a considerable contribution of a leptonic component. By modelling the gamma-ray halos powered by middle-aged pulsars in our Galaxy with taking into account the magnetic field configuration and the interstellar radiation field in the Galaxy, we demonstrate that the collective contribution of pulsar halos can account for the excess in the measured diffuse gamma-ray emission with respect to the predicted flux from CR-ISM interactions.

Session 8.

SNRs and PWNe as PeVatrons – Oral Talks

Maximum energy cosmic rays from galactic supernovae: simulations of quasi-parallel and -perpendicular shocks

Oral Talk

Emily Simon, Damiano Caprioli, Colby Haggerty, Brian Reville

University of Chicago, USA

Abstract

The galactic component of the cosmic ray (CR) energy spectrum is thought to be dominated by particles accelerated at shock waves from supernova remnants (SNRs). However, both observations and analytical estimates indicate that SNRs may only be capable of accelerating CRs to hundreds of TeV, a factor of 10 shorter than the galactic cutoff around several PeV. We employ a novel setup for hybrid particle-in-cell simulations to study the far upstream of the shock over longer time scales, allowing us to the see the triggering and saturation of the non-resonant Bell instability, and to study the maximum energy CRs it is possible to accelerate. We also study the sensitivity of maximum energy on the angle between the shock normal and the initial magnetic field with implications for quasi-perpendicular regions in SN 1006 and other SNRs.

The what, where, and who of Galactic PeVatrons probed by high-energy observations

Invited Talk

Fabio Acero

CEA-Saclay FSLAC, France

Abstract

In the last decade, significant progress has been made on the question of the nature and energetics of particles accelerated in SNRs and PWNe by combining the gamma-ray observations provided by the Fermi-LAT at GeV and Cherenkov telescopes at TeV. However, in order to explain the Galactic cosmic-ray spectrum, Galactic accelerators should be able to generate particles up to PeV (10^{15} eV) energies, and this evidence has been so far lacking. Water Cherenkov detectors, in particular LHAASO, have provided a transformational view on the gamma-ray sky at 100 TeV, giving new insights on the nature of Galactic PeVatrons. This contribution will discuss the different ways our community is defining PeVatron sources, where we expect to find them, and how our focus has gradually shifted from SNRs to PWNe as plausible PeV accelerators. An overview of the recent GeV and multi-TeV measurements motivating this shift will be presented, followed by a discussion of the advancements that will be made with the next generation Cherenkov Telescope Array (CTA).

LHAASO observations of the SNR Cassiopeia A

Oral Talk

Ruizhi Yang

University of Science and Technology of China, China

Abstract

Supernova remnants (SNRs) have been considered the prime sources of Galactic cosmic rays (CRs). But whether SNRs can accelerate CR protons to PeV energies and thus dominate CR flux up to the knee is currently under intensive theoretical and phenomenological debate. The direct test of the ability of SNRs to operate as CR PeVatrons can be provided by ultrahigh-energy (UHE; $E\gamma \geq$ 100 TeV) γ-rays. In this context, the historical SNR Cassiopeia A (Cas A) is considered one of the most promising target for UHE observations. This paper presents the observation of Cas A and its vicinity by the LHAASO KM2A detector. The exceptional sensitivity of LHAASO KM2A in the UHE band, combined with the young age of Cas A, enabled us to derive stringent model-independent limits on the energy budget of UHE protons and nuclei accelerated by Cas A at any epoch after the explosion. The results challenge the prevailing paradigm that Cas A-type SNRs are major suppliers of PeV CRs in the Milky Way.

Supernova remnants in stellar clusters: particle acceleration

Oral Talk

Iurii Sushch[1], Pasquale Blasi[1], and Robert Brose[2]

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[2]DCU, Dublin, Ireland

Abstract

Supernova remnants (SNRs) are widely considered as the main sites of acceleration of cosmic rays in our Galaxy. Nevertheless, the ability of particles to reach PeV energies in these sources is elusive and lacks observational evidence. Theoretical predictions suggest that only a small subclass of very young SNRs evolving in dense environments could potentially satisfy the necessary conditions to accelerate particles to PeV energies. In this respect, the explosion of an SNR in the stellar cluster and subsequent expansion into the collective wind generated by stars of the cluster seems to be quite promising. In this work we critically assess the efficiency of particle acceleration at the shock of the SNR exploded at the edge of the stellar cluster. Using both analytic and numerical approaches we investigate the spectrum of accelerated particles and maximum achievable energy taking into consideration the self-generated magnetic turbulence as well as pre-existent turbulence in the collective stellar cluster wind. We find that similar to isolated SNRs, acceleration to PeV energies is plausible only for extreme conditions achievable only for a small subset of SNRs.

Hadronic particle acceleration in the supernova remnant SN 1006 as traced by Fermi-LAT observations

Oral Talk

Marianne Lemoine-Goumard, F. Acero, J. Ballet, M. Miceli

Université de Bordeaux, France

Abstract

The supernova remnant SN 1006 is a powerful source of high-energy particles, evolving in a tenuous environment except two atomic clouds in the North-West and South-West limb, respectively. We used 14 years of Fermi-LAT data to perform a spatially resolved spectral analysis of the remnant. While previous studies detected only the North-East limb, this increased dataset allows the significant detection of both limbs. The North-East limb displays a hard gamma-ray spectrum characteristic of inverse Compton emission. In the opposite, the broad-band modeling of the softer emission detected in the South-Western limb favors a scenario in which the gamma rays are dominantly produced via proton-proton interaction, confirming that SN 1006 is an efficient proton accelerator. The major constraints provided by the new Fermi-LAT data as well as a comparison with the other shell-type remnants detected by the LAT will be presented during this talk.

Multi-wavelength observations of Galactic PeVatrons

Invited Talk

Kaya Mori

Columbia University, USA

Abstract

The recent discovery of over 40 ultra-high-energy (UHE; > 100 TeV) gamma-ray sources and neutrino emission in the Galactic Plane has provided compelling evidence for Galactic PeVtrons, which are capable of accelerating particles to 10^{15} eV or beyond. These findings mark a significant paradigm shift in high-energy astrophysics from "Do PeVatrons exist in our galaxy" to "What are the Galactic PeVatrons?" As evident from previous studies of Galactic TeV sources, multi-wavelength observations are crucial to identifying the Galactic PeVatrons. In particular, a combination of broad-band spectral energy distribution (SED) and morphological data can serve as a powerful diagnostic tool for probing their particle acceleration and emission mechanisms. This presentation will review recent multi-wavelength observation campaigns of Galactic PeVatron sources, primarily focusing on X-ray observations combined with radio, GeV, and TeV data. I will highlight (1) multi-wavelength observations of pulsar wind nebulae associated with UHE sources, (2) multi-epoch NuSTAR hard X-ray observations of young supernova remnants such as Cassiopeia A and Kepler, and (3) XMM-Newton surveys of unidentified UHE sources, including the so-called dark accelerators, as well as future prospects in X-ray astrophysics of Galactic PeVatrons.

Session 8.

SNRs and PWNe as PeVatrons – Posters

Fast Blue Optical Transients as cosmic-ray sources

Poster

Robert Brose[1], Iurii Sushch[2], Jonathan Mackey[3]

[1]Dublin City University, Ireland
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Abstract

Fast Blue Optical Transients (FBOTs) are luminous short-lived events, that strongly emit at blue colors around their peak in the optical waveband. The late-time emission shows similarities to supernovae (SNe) associated with long GRBs and superluminous SNe but the origin of FBOTs is not yet understood. However, the fast rise-time of the optical emission of a few days indicates fast-moving ejecta interacting with dense material (CSM) close to the "central engine". The high luminosities in the optical, radio and x-ray bands suggest efficient particle acceleration due the high mass passing through the shock and consequently the possibility for high cosmic-ray currents driving magnetic-field growth and consequently acceleration. The evolution of the radio-emission is very similar for both FBOTs and objects like e.g. Type-IIn supernovae where shocks interact with material from previous LBV eruptions after 10s-1000s of days. In both cases, the CSM-interaction is detected strongly in optical wavelengths and followed by bright radio-emission with a substantial delay of 10s-100s of days for Type-IIn SNe and <10 days for FBOTs. We extrapolate our existing numerical models for Type-IIn SNe to earlier shock-CSM interactions as similarities in the acceleration process between the SNe and FBOTs can be expected based on the observational signatures. We obtain the gamma-ray luminosity and maximum energy of FBOTs and find that only a small fraction of 10-3% of the explosion energy gets converted to cosmic-rays. At the same time, the maximum energy easily exceeds a few PeV. Strong gamma-gamma absorption hinders a detection with current generation instruments.

The Maximum Energy of Shock-Accelerated Cosmic Rays

Poster

Rebecca Diesing

Institute for Advanced Study & Columbia University, USA

Abstract

Identifying the accelerators of Galactic cosmic ray protons (CRs) with energies up to a few PeV (10^{15} eV) remains a theoretical and observational challenge. Supernova remnants (SNRs) represent strong candidates, as they provide sufficient energetics to reproduce the CR flux observed at Earth. Moreover, multi-wavelength emission observed from their forward shocks indicates that SNRs are powerful particle accelerators. However, it remains unclear whether they are capable of accelerating particles up to PeV energies, particularly after the very early stages of their evolution. This uncertainty has prompted searches for other source classes and necessitates comprehensive theoretical modeling of the maximum proton energy, $E_{\rm max}$, accelerated by an arbitrary shock. While analytic estimates for $E_{\rm max}$ have been put forward in the literature, they do not fully account for the complex interplay between particle acceleration, magnetic field amplification, and shock evolution. Using a multi-zone, semi-analytic model of particle acceleration based on kinetic simulations, we place constraints on $E_{\rm max}$ for a wide range of astrophysical shocks, using SNRs as a benchmark. In particular, we develop relationships between $E_{\rm max}$ and the shock velocity, size, and ambient medium. Our results serve as a reference for modelers seeking to quickly produce a self-consistent estimate of the maximum energy accelerated by an arbitrary astrophysical shock.

Pulsar Wind Nebulae and their halos observed in TeV and PeV gamma rays

Poster

Yves Gallant, Karim Sabri, Justine Devin

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Abstract

TeV gamma-ray sources associated with pulsars constitute the largest class of sources revealed by the H.E.S.S. Galactic Plane Survey. They are generally interpreted as Pulsar Wind Nebulae (PWNe), in which electrons and positrons are confined by the nebular magnetic field, and the dominant transport mechanism is advection. More recently, gamma-ray detectors such as HAWC and LHAASO, which are more sensitive to extended emission, have revealed sources associated with typically older pulsars, with emission in some cases extending towards PeV energies. These are generally interpreted as PWN halos, dominated by escaped electrons and positrons diffusing in the interstellar medium. We examine the observed gamma-ray properties of PWNe and halo candidates, including their extension and offset from the pulsar, focusing on the distinction and transition between old PWNe and halos. We interpret the observations in terms of a leptonic model of late PWN and halo emission, including electron and positron transport, radiative losses, and pulsar evolution. We discuss the capabilities of such sources to act as leptonic PeVatrons. We outline the prospects for the next-generation TeV gamma-ray observatory, CTAO, to shed light on these issues.

Radio-continuum view of PeVatrons

Poster

Sanja Lazarevic[1,2], Miroslav D. Filipovic[1], Gavin Rowell[3], Philip Edwards[2] and Shi Dai[1]

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Abstract

Galactic cosmic rays are charged particles with energy reaching 1 to about 100 PeV. They rain down on Earth after having been accelerated somewhere in interstellar space and are the most energetic particles known in our Galaxy. Although they were discovered just over 100 years ago, cosmic ray origin remains one of the longest unanswered questions of modern physics. With recent advances in gamma-ray telescopes, HESS and CTA, coupled with new-generation radio surveys obtained by ASKAP and MeerKAT, it is now finally possible to probe the origin of these PeV cosmic rays. In this poster, I will present the case of the two most prominent HESS PeVatrons: J1641-463 and J1646-458.

Multi-Messenger Modeling of the Monogem Pulsar Halo

Poster

Youyou Li, Oscar Macias, Shinichio Ando, Jacco Vink

GRAPPA/University of Amsterdam, The Netherlands

Abstract

The High-Altitude Water Cherenkov Telescope (HAWC) has detected TeV halos associated with two nearby pulsars/pulsar wind nebulae (PWN) - Geminga and B0656+14. These TeV halos extend up to tens of parsecs from the central accelerators, indicating that the diffusion of electrons and positrons in the interstellar medium has been suppressed by two orders of magnitude. Although Geminga and B0656+14 are at similar distances and in the same field of view, they have distinct histories. Notably, B0656+14 probably still resides within its parent supernova remnant, the Monogem Ring, which can be observed in X-rays. In this work, we perform high-resolution simulations of the propaga- tion and emission of relativistic lepton pairs around B0656+14 using a two-zone diffusion model within the GALPROP framework. We compared the predicted inverse-Compton spectrum to the observations made by HAWC and Fermi-LAT and found physically plausible model parameters that resulted in a good fit to the data. Additionally, we estimated the contribution of this TeV halo to the positron flux observed on Earth. We conclude that future observations of the TeV halo and its synchrotron emission counterpart in radio frequencies and X-rays will be crucial to distinguish between various possible model parameter configurations.

The Manatee Nebula W50-SS433: a Galactic PeVatron?

Poster

Brydyn Mac Intyre[1], S. Zhang[2], S. Safi-Harb[1], K. Mori[2], for the W50 Collaboration

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Abstract

We present a comprehensive X-ray investigation of the W50 SNR, commonly known as the 'Manatee' Nebula, powered by the microquasar SS433. This system serves as a unique testing ground for exploring several fundamental astrophysical phenomena. Although W50 is categorized as a supernova remnant, it boasts an unconventional double-lobed structure that is believed to be linked to the emissions from SS433's jets. Our study leveraged observations from NuSTAR and XMM-Newton, concentrating on the inner western lobe of W50 and continues previously published work on the eastern lobe. Within the western lobe, robust evidence of hard non-thermal X-ray emissions extending up to roughly 20 keV has been successfully identified. These emissions originate from a compact, knotty area referred to as the 'Head', positioned approximately 17 arcminutes (equivalent to 26.5 pc when considering a distance of 5.5 kpc) to the west of SS433. The analysis has further allowed the determination of the photon index, which stands at 1.55 across the 0.5-20 keV energy range. Moving westward from SS433, the photon index gradually steepens, ultimately reaching the X-ray bright 'w2' region, where a photon index of 2.10 is reached. The distinct hard X-ray knots observed mirror what is observed in the eastern lobe and serve as clear markers for sites of particle acceleration within the jet. Their synchrotron emission implies an equipartition magnetic field strength on the order of about 15 μG. Notably, the unusually hard spectral index originating from the 'Head' mirrors hard X-ray emission seen in other astrophysical objects such as blazars and pulsar wind nebulae.

Pulsar Wind Nebulae and PeVatrons: A Case Study of PWN G309.92-2.51

Poster

Isabel Sander[1], Alan Nguyen[2], Moaz Abdelmaguid[3], Jooyun Woo[4], Samar Safi-Harb[1], Kaya Mori[4], Joseph Gelfand[3], and Hongjun An[5]

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Abstract

Although cosmic rays (CRs) were first identified over a century ago, their origins remain mysterious, specifically for those with energies that exceed 1 peta-electronvolt (PeV). The search for the source of these Galactic CRs has led to the investigation of Pulsar Wind Nebulae (PWNe), which are formed by the jets of energetic, rotation-powered pulsars. PWNe are potential PeVatrons, meaning they could be capable of accelerating particles up to PeV energies. Utilizing data from the Chandra, XMM-Newton, NuSTAR, H.E.S.S., and Fermi Gamma-Ray Space telescopes, we analyze Pulsar Wind Nebula G309.92-2.51. With an associated TeV source, HESS J1356-645, this PWN presents a promising candidate for a galactic PeVatron. Our primary goal, employing a multi-wavelength approach, is to determine the maximum particle energy reached in PWN G309.92-2.51 and compare it with expected values of a PeVatron. Our methodology begins with separate data reduction and analysis for each dataset. We perform timing analysis on both the XMM-Newton and NuSTAR telescope data to remove pulsed photons, followed by combined spectroscopy to determine the photon index of the PWN in the NuSTAR energy range. With all available data, we create a spectral energy distribution (SED) and use a dynamical model for the evolution of the PWN inside the supernova remnant$^+$. With the results from our SED analysis, we aim to enhance our understanding of PWNe as potential PeVatrons and uncover clues to the origin of galactic CRs.

Search for molecular clouds associated with PeVatrons by the Nobeyama 45-m radio telescope: the case of LHAASO J0341+5258

Poster

Naomi Tsuji, Shunya Takekawa

Kanagawa University, Japan

Abstract

The origin of PeV cosmic-ray factories ("PeVatron") remains as a long-standing problem in high-energy astrophysics. Recent progress in water Cherenkov telescopes, such as HAWC and LHAASO, opened up a new era of the study of PeVatron. The first LHAASO catalog includes 43 gamma-ray emitters detected with >0.1 PeV (Cao et al. 2023), and thus they are considered as PeVatron candidates. Most of these LHAASO sources are poorly explored in other wavelengths and yet to be identified. Such high-energy gamma rays (> 0.1 PeV) may favor the hadronic origin (i.e., pion decay) rather than the leptonic origin (i.e., inverse Compton scattering), of which high-energy photons are suppressed due to the Klein-Nishina effect. In the hadronic case, gamma rays are expected to coincide with dense environments, such as molecular clouds. Using the Nobeyama Radio Observatory 45-m radio telescope, an extensive search for molecular clouds associated with PeVatrons is currently underway and planned. Our initial investigation, focusing on the PeVatron source LHAASO J0341+5258, has revealed the presence of molecular clouds within the gamma-ray emitting region. In the poster, we report detailed findings of LHAASO J0341+5258 and outline our observation plan of the other PeVatron sources.

Revisiting Cassiopeia A after a decade: the first spatially resolved synchrotron X-ray variability above 15 keV by NuSTAR

Poster

Jooyun Woo[1], Aya Bamba[2], Brian Grefenstette[3], Charles Hailey[1], Brian Humensky[4], Kaya Mori[1], Reshmi Mukherjee[5], Toshiki Sato[6], Elizabeth Spira-Savett[5], Tea Temim[7], Naomi Tsuji[8]

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Abstract

As the youngest (∼350 years old) nearby (∼3.4 kpc) Galactic core-collapse supernova remnant (SNR), Cassiopeia A (Cas A) is a rare test bed for a plethora of astrophysical theories. Of particular interest is cosmic ray acceleration at Cas A. A general argument is that supernovae and their remnants may account for a large fraction of the Galactic cosmic ray protons up to a few PeV. Ultra-high-energy (above 100 TeV, UHE) gamma rays from pion decays are the smoking gun of proton acceleration; however, the UHE flux of Cas A and other Galactic SNRs falls below the sensitivity of the current UHE observatories. The limited angular resolution of gamma-ray telescopes (>0.1°) poses another challenge in locating the proton acceleration sites in SNRs. An alternative yet unambiguous evidence of particle acceleration lies in sub-arcminute-scale hard X-ray observation of synchrotron emission from the ultrarelativistic primary and secondary leptons. The leptons are accelerated to such high energies at the SNR blast wave in a strongly amplified (>100s uG) magnetic field. While the strong magnetic field is optimal for efficient particle acceleration, it also entails extremely fast synchrotron cooling for leptons. The interplay between these two competing phenomena can exhibit year-scale variability of hard X-ray emission in young SNRs, as observed with Chandra in RX J1713.7-3946, Tycho, and Cas A. An important caveat of those observations is that the X-ray continuum probed by Chandra (below 6 keV) must contain non-negligible thermal emission, limiting the attribution of the observed variability to particle acceleration and synchrotron cooling. In this work, we present, for the first time, the spatially resolved synchrotron X-ray variability of Cas A observed by NuSTAR in 15 - 50 keV, safely eliminating the possibility of thermal contribution. We compare our new NuSTAR observation of Cas A with the 2.4 Ms of archival NuSTAR data from 10 years ago to measure the changes in the synchrotron flux and spectral shape from different parts of the remnant. We discuss the implications of these results for the recent theory of modified non-linear diffusive shock acceleration.

Session 9.

SNR/PWN/Compact Objects Associations, Interaction and Evolution – Oral Talks

High-Resolution X-Ray Spectroscopy of Supernova Remnants: From Dispersive Spectrometers to Microcalorimeters

Invited Talk

Satoru Katsuda

Saitama University, Japan

Abstract

Resolving individual spectral lines and line shapes is critically important to derive information about supernova remnants. This has been demonstrated by high-resolution spectroscopy with past dispersive X-ray spectrometers including Einstein/FPCS, XMM-Newton/RGS, and Chandra/HETG. However, these dispersive spectrometers are slitless, and work only for small objects with angular sizes less than a few arcminutes. Given that most of the Galactic supernova remnants are extended by more than a few arcminutes, observable targets with nondispersive spectrometers are quite limited. This limitation has been expected to be broken with non-dispersive microcalorimeters. The microcalorimeter aboard the Hitomi satellite indeed showed exciting spectra from a few astrophysical objects like Perseus Cluster, but its short lifetime did not allow us to obtain such data from supernova remnants. The XRISM satellite, launched on September 7th in 2023, carries a microcalorimeter with nearly the same performance as that of Hitomi, resuming the high-resolution X-ray spectroscopy of extended sources. XRISM already observed several supernova remnants including Cas A, Tycho, Kepler, SN 1006, and N132D, demonstrating the power of the microcalorimeter. I will present the current status of the high-resolution X-ray spectroscopy with dispersive spectrometers, and hopefully will show some fresh results from XRISM.

New constraints on the Pulsar Wind Nebula in SN 1987A from multiwavelength observations and MHD modeling

Oral Talk

Emanuele Greco[1], Marco Miceli, Salvatore Orlando, Barbara Olmi, Lei Sun, Jacco Vink, Shigehiro Nagataki, Masaomi Ono, Akira Dohi, Vincenzo Sapienza, Giovanni Peres, and Fabrizio Bocchino

[1]INAF-Osservatorio Astronomico di Palermo, Italy

Abstract

After more than 30 years of elusive detection, in the last five years new pieces of evidence across the electromagnetic spectrum have suggested the existence of a neutron star in the heart of SN1987A. In this talk, I will go through the results obtained in the radio band through the ALMA telescope, in the X-rays with NuSTAR and in the infrared through JWST and I will present the Spectral Energy Distribution (SED) modeling of the emission of the compact object based on the available observational constraints. Starting from the results obtained in the X-rays, I will show that the Pulsar Wind Nebula (PWN) scenario is the only one that provides a coherent picture at all wavelenghts, being able to account for the emission observed in the radio, infrared and X-ray band and being compatible with the known upper limits.

Pulsar Wind Nebulae phenomenology and evolution at and beyond reverberation

Oral Talk

Diego F. Torres[1], R, Bandiera[1], N. Bucciantini[1], and B. Olmi[2]

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Abstract

The vast majority of the pulsar wind nebulae (PWNe) present in the Galaxy are middle-aged systems that have gone already, or are about to go through a strong interaction of the PWN itself with the supernova remnant (SNR), a process referred to as reverberation. Modelling these systems can be quite complex and numerically expensive, due to the non-linearity of the PWN-SNR evolution even in the simple one-dimensional (1D)/one-zone case. In radiation models in fact, the details of such reverberation are either ignored, or, in a few cases, described in simplified ways. I will present some of the results of an effort to understand reverberation of PWNe in detail. In particular, I will discuss the validity of some of the usual assumptions taken, e.g., how thin is the PWN boundary or how constant (or Sedov like) is the pressure outside the PWN. I will also introduce a new numerical technique that couples the numerical efficiency of the one-zone thin shell approach with the reliability of a full 'Lagrangian' evolution that is able to correctly reproduce the PWN-SNR interaction during the reverberation and to consistently evolve the particle spectrum beyond. Our approach enable us for the first time to provide reliable spectral models of the later compression phases in the evolution of PWNe. While in general, we found that the compression is less extreme than that obtained without such detailed dynamical considerations, leading to the formation of less structured spectral energy distributions, we find that a non-negligible fraction of PWNe will experience a strong super-efficient phase, with the optical and/or X-ray luminosity exceeding the spin-down power of the pulsar at the time.

The zoo of isolated neutron stars

Invited Talk

Alice Borghese

INAF, Osservatorio Astronomico di Roma, Italy

Abstract

Neutron stars have shown diverse characteristics, leading us to classify them into different classes. In this talk, I will focus on the observational properties of isolated neutron stars: from magnetars, the strongest magnets we know of, to central compact objects, the so-called anti-magnetars, stopping by the rotation-powered pulsars and X-ray dim isolated neutron stars. Moreover, I will show you how some sources have exhibited features straddling those of different groups. I will then finish with some considerations on possible evolutionary links between neutron star families.

Discovery of new oxygen-rich supernova remnants

Oral Talk

Timo Kravtsov

ESO, Chile & University of Turku, Finland

Abstract

Extragalactic SNe may continue evolving for years before fading too much to be observed. In some cases strong emissions of forbidden oxygen have been observed, including doubly ionized oxygen emission. For example, SN2012au exhibited oxygen-dominated spectra six years after the cataclysmic explosion. These objects are reminiscient of the unusual SNR 4449-1. This remnant fall within the 'O-rich SNR' subclass of remnants, which are generally brighter than normal SNRs and are thought to be younger. Here, I introduce a new method to find SNRs in nearby galaxies using the 3D spectroscopic capabilities of MUSE, based on a search for unresolved broad-line emission sources in visible light. The survey has led to a discovery of over 300 new extragalactic SNR candidates, but additionally seven new O-rich SNRs, almost doubling the sample of these rare SNRs. I will present the discovery and initial characterisation of the new O-rich SNRs, comparing them to literature events and observations of SNe several years and decades after discovery. Significant similarities are found between O-rich SNRs and old core-collapse SNe, strengthening claims that O-rich SNRs are relatively young. These new O-rich events have also been detected at X-ray and mid-IR wavelengths with Chandra and JWST respectively.I will also present recent efforts into modeling these objects, demonstrating how these objects may be powered by a pulsar wind nebula embedded in O-rich ejecta of the SN. Our new sample of O-rich events will provide additional clues as to their origin and their connection to more evolved SNRs.

Session 9.

SNR/PWN/Compact Objects Associations, Interaction and Evolution – Posters

Late-time X-ray observations Core-Collapse Supernovae - constraints on emission from compact objects and CSM interaction

Poster

Julia Ahlvind and Josefin Larsson

KTH Royal Institute of Technology, Sweden

Abstract

Late-time X-ray observations of core-collapse supernovae (SNe) offer unique insights into the formation of compact objects and the interaction with the circumstellar material (CSM). In this study, we present the findings of an extensive analysis of late-time X-ray emission from >100 nearby SNe, comprising >400 individual X-ray observations. The sample consists of observations taken by Chandra, XMM-Newton, Swift, and NuSTAR at epochs ranging from ∼200 days to ∼100 years after explosion. In most cases, the SNe were observed by chance within the field of view of other targets. We measure the luminosities, or obtain upper limits in the case of non-detections, for the SNe and compact objects, where the assumed power-law emission from the compact object is estimated while accounting for ejecta absorption effects. We use the results of 3D neutrino-driven explosion models to account for this ejecta absorption. We find that approximately 10% of the SNe are detected at late times, and ∼5% of the sample show emission that can be attributed to compact objects in the case of favourable viewing angles with negligible ejecta absorption. We further use the luminosity limits to constrain the physical properties of the compact objects created in the explosions.

Multi-Wavelength Modelling of the Pulsar Wind Nebulae Kes 75 & HESS J1640-465

Poster

Abdelmaguid M. Moaz[1], Joseph Gelfand[1], Jason Alford[1], Samayra Straal[1] and Eric Gotthelf[2]

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[2] Columbia University, USA

Abstract

Powered by energetic pulsars, Pulsar Wind Nebulae (PWNe), exhibit emissions spanning the entire electromagnetic spectrum, showcasing diverse morphologies and spectral characteristics across different wavelengths. The evolution of PWNe is dependent on the progenitor neutron star, the relativistic outflows driven by its rotational energy, the surrounding medium, magnetic fields, and particle energies. Moreover, PWNe serve as significant sources for accelerating particles to PeV energies, playing a vital role in explaining the origins of galactic cosmic rays. In this talk, I will discuss our results from the multi-wavelength SED modelling of two systems; HESS J1640-465 – possibly the most TeV luminous gamma-ray source in our galaxy – and Kes 75, a PWN powered by an energetic rotation powered pulsar with strong dipole magnetic field strength that displays magnetar-like X-ray outbursts, flux variability and timing irregularities.

A-MUSE-ing Views of the Central Environment of the Vela Jr. and 1E0102-72.3 Supernova Remnants

Poster

Janette Suherli[1], Samar Safi-Harb[1], Ivo R. Seitenzahl[2], Parviz Ghavamian[3], Wynn C. G. Ho[4], Chuan-Jui Li[5], Ashley J. Ruiter[2], Ralph S. Sutherland[6] and Frederic P. A. Vogt[7]

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Abstract

Integral field spectroscopy is a powerful technique in optical astronomy that enables us to obtain a spectrum at every spatial position of an object. It is a highly effective tool for studying structurally-complex astronomical objects such as supernova remnants (SNRs). Using the Multi-Unit Spectroscopic Explorer (MUSE) installed on ESO's Very Large Telescope, we explored the environment of the central compact object (CCO) within the Vela Jr. SNR and the CCO candidate within the SNR 1E0102-72.3, with the goal to address their puzzling nature. By probing CCOs outside of the X-ray regime using integral field spectroscopy, we provide a new perspective on their environment, progenitors, and the properties of their host SNRs.