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

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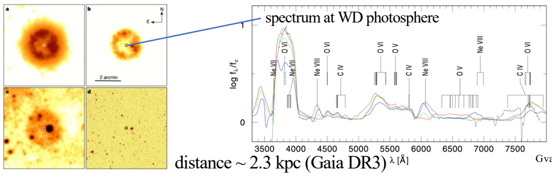
Abstract

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 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.

Discovery of Massive White Dwarf WD J005311

- Massive White Dwarf WD J005311 with high rotation velocity surrounded by H, He-poor nebula was reported in 2019.
- These features support that WD J005311 was formed by WD-WD binary merger scenario suggested by Schwab et al. 2016.



distance ~ 2.3 kpc (Gaia DR3)

The width & height of the wind line spectrum ⇒	$\dot{M} = (3.5 \pm 0.6) \times 10^{-6}\, M_\odot\, \mathrm{yr}^{-1}$ $v_\infty = 16,000 \pm 1,000\, \mathrm{km\, s^{-1}}$
magnetohydro model ⇒	WD mass$\sim 1.1 - 1.3 M_\odot$ Kashiyama+ 2019

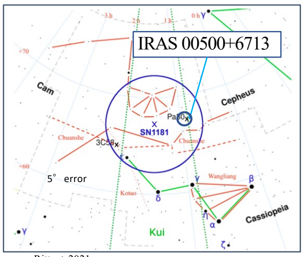
A leading candidate of SNR 1181

distance ~ 2.3 kpc (Gaia DR3)

- The on-sky location fits historical reports of SN 1181
- Radius and velocity of the remnant

→ WD was formed ~1000 yr ago

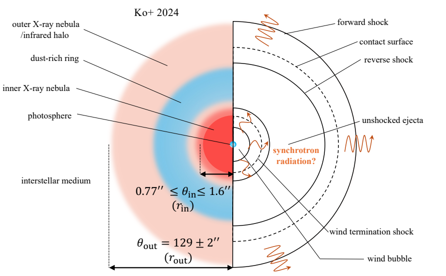
We aim to understand the properties of the WD merger by constructing a model of IRAS 00500+6713 **assuming this nebula is SNR 1181.**

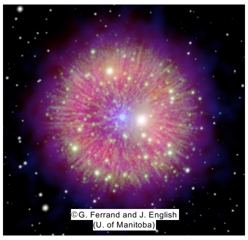


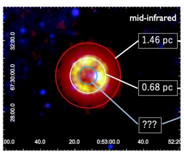
Ritter+ 2021

Multi-layer structure of SNR 1181

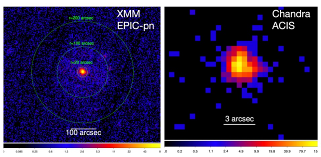
- Observations show the nebula consists of multi-layers
- SN ejecta + ISM → outer shocked region
- Wind + SN ejecta → inner shocked region







Mid-infra Obs. (Oskinova+ 2020)



X-ray Obs. (Ko+ 2023)

Theoretical modeling of SNR 1181

- We calculate the outer shock evolution using self-similar solution by Chevalier+82
  - We search for a parameter $M_{\rm ej}$ and $E_{\rm ej}$, which can reproduce the spread of the shock region and the EM.
  - X-ray analysis → $EM = n_e n_{ion} V = 3.7 \times 10^{54}$ /cm^3
  - We obtain the following relation:

$$\left(\frac{E_{\rm ej}}{10^{48}\,{\rm erg}}\right)^{-1/2}\left(\frac{M_{\rm ej}}{0.5\,M_\odot}\right)^{1/6} = 0.97\left(\frac{{\rm EM_{out}}}{3.7\times10^{54}\,{\rm cm^{-3}}}\right)^{-1/6}.$$

- We calculate the inner shock evolution using thin-shell approximation and solving the following eqs:

$$M_{\rm sh,in} = M_{\rm sh,in,w} + M_{\rm sh,in,ej},$$
$$\frac{d}{dt}M_{\rm sh,in,w} = \dot{M}_{\rm w},$$
$$\frac{d}{dt}M_{\rm sh,in,w} = 4\pi r_{sh}^2 \rho(r_{sh})(v_{sh} - v_{ej}).$$

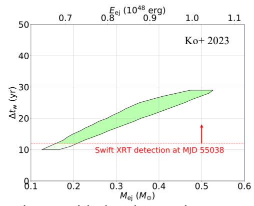
$$M_{\rm sh,in}\frac{dv_{\rm sh}}{dt} = 4\pi r_{\rm sh}^2[p_{\rm w} - \rho_{\rm ej}(v_{\rm sh} - v_{\rm ej})^2] - \frac{GM_{\rm sh,in}M_*}{r_{\rm sh}^2},$$
$$\frac{d}{dt}\left[\frac{4\pi r_{\rm sh}^3}{3}\frac{p_{\rm w}}{\gamma - 1}\right] = L_{\rm w} - p_{\rm w} \times 4\pi r_{\rm sh}^2 v_{\rm sh},$$

- If we assume the wind started blowing soon after SN1181, we cannot reproduce the spread of the region.
- The wind must start blowing recently (Maybe due to the KH contraction or ejecta accretion).
- We calculate the evolution of the thin shell and estimate the spread and EM of the inner region for each parameter set of $M_{\rm ej}$ and $\Delta t_{\rm w}$ ($\Delta t_{\rm w}$ refers to how many years ago the wind started blowing from now.).
- We compare these values with the observation and constrain the parameters ($M_{\rm ej}, E_{\rm ej}, \Delta t_{\rm w}$).

Results

- We constrain the parameter sets, which are consistent with the typical values of SN Iax.
- This result strongly supports the assumption of IRAS 00500+6713 is SNR 1181.

$12\,{\rm yr} < \Delta t_w < 30\,{\rm yr}$
$0.18 M_\odot < M_{\rm ej} < 0.53 M_\odot$
$0.77\times10^{48}\,{\rm erg} < E_{\rm ej} < 1.1\times10^{48}\,{\rm erg}$



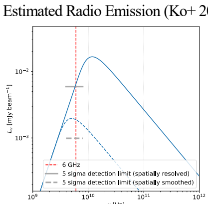
Conclusions

- We construct a theoretical model of SNR 1181 which is consistent with the observations
- We estimate the ejecta mass and the explosion energy of SN 1181:
  - $0.18 M_\odot < M_{\rm ej} < 0.53 M_\odot$, 0.77×10^{48} erg $< E_{\rm ej} < 1.1\times10^{48}$ erg
  - These parameters are consistent with typical values of SN Iax
- We find the wind from the central WD started blowing recently : $12\,{\rm yr} < \Delta t_w < 30$ yr
- We also find the mass of the progenitor model is $1.3 - 1.8\,M_\odot$, which is consistent with the hypothesis that the progenitor system is a binary of ONe WD and CO WD.

Future works

- To confirm the wind started blowing recently
  - XRISM observation to estimate the expanding velocity of the inner shocked region
  - Constructing a wind blowing model using MESA.
- Radio observation
  - The proposal was accepted → the spread of the central source
- Multi-dimension modeling

Estimated Radio Emission (Ko+ 2024)



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- We use the X-ray data which was observed by Oskinova.

The time evolution of SNR 1181 from the explosion