Models for supernova remnants with reverse shock emission in the SMC

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INTRODUCTION

A supernova remnant (SNR) is the cavity of hot plasma in the interstellar medium (ISM) created by the shock waves from an energetic explosions (a supernova or SN) at the end of life of a star. Type Ia SNRs are created by thermonuclear explosions of white dwarf, whereas core-collapse (CC) explosions are created by the inward collapse of the cores of a massive stars. SNRs are bright emitters in X-ray via hot plasma thermal (bremsstrahlung and line) emission, and in radio via synchrotron emission of relativistic electrons spiralling in magnetic fields. Some SNRs are bright in optical line emission, when the shock encounters a dense interstellar cloud, or in infrared emission, from shock heated thermal dust emission.

SNe and SNRs have a profound impact on galaxies: they eject the elements created by fusion in stellar interiors during a star's lifetime into the ISM, resulting in the increase in metallicity in a galaxy with time. The ejected kinetic energy is a major contributor to motions of the ISM, including mixing in the ISM; regulating star formation in the ISM (both in stimulating new star formation and inhibiting it); and in driving galactic winds which affect the long-term evolution of a galaxy and enrich the circum-galactic environment.

X-ray observations of SNRs via their X-ray spectra give measures of the elemental composition of the shocked ISM and of the shocked material ejected in the explosion, allowing studies of the ISM and of the material formerly in stellar interior. To interpret the X-ray spectra, and thus obtain information on the ISM and progenitor of the explosion, requires models of SNR evolution (e.g. Truelove and McKee 1999). Here we use SNR evolution models developed by Leahy et al (2017, 2019) to interpret X-ray observations of SNRs in our neighboring galaxy, the Small Magellanic Cloud (SMC).

J0104-7219 (1E 0102.2-7219)

Here we focus on models for 1E 0102.2-7219 (MCSNR J0104-7201). The SNR X-ray spectrum properties were derived from the work of Alan et al (2019). For the forward shock (FS), we use the thin outer Shell region and correct it by multiplying the emission measure (EM) by a factor of 1.6 to correct for the area of complete thin circular shell that was not measured. We multiply by an additional factor of 2 to correct for the FS emission which appears projected in front of the interior (RS) emission from the SNR.

For 1E 0102.2-7219 we calculate the RS mean temperature and abundances by averaging over the ~160 regions analyzed by Alan et al (2019), after removing the outermost regions which are likely dominated by the FS and removing overlapping regions near the center of the SNR (see their Fig. 5b). The RS EM is obtained by summing over these same regions, then multiplying by a factor 1.7 to account for the areas not analyzed. The resulting RS properties and their upper and lower limits are given in the Table below.

kT_keV	kT-	kT+	ne*t(1e11)	ne*t-	ne*t+	EM(1e57)	EM-	EM+	O	O-	O+	Ne	Ne-	Ne+	Mg	Mg-	Mg+	Si
0.772844	0.719981	0.875634	39.81298	30.92961	52.47257	565.692	552.8009	581.2869	0.87476	0.786117	1.034137	1.628061	1.476587	1.914245	0.678665	0.603271	0.815153	0.151692

A series of models for uniform (s=0) and CSM wind (s=2) environments are calculated using the latest version of SNRpy (Leahy et al, 2019). These models yield large ages for s=0 models (3000 to 6000 yr, depending on n) which is contrary to the expansion velocity estimate of the age from Hughes et al (2000) of ~1000 yr. The s=2 models all give a low age ~300 to 700 yr (see Table below). This is expected because the FS slows with time giving a smaller age that the simple linear expansion estimate of ~1000 yr. The Table gives results for s=2 models with different n and ejecta mass, including the predicted temperature and EM for the RS. The s=2 models all have high explosion energy (7e51 to 4e52 erg, with energy increasing as the ejected mass increases from 5 Msun to 40 Msun). The stellar wind q is close to 6e13 g/cm, which yields a high, but feasible, mass loss rate of 3.6e-4 Msun/yr for a wind velocity of 300 km/s.

FS Radius(pc)	FS Temp.(keV)	FS Emission Measure(cm^-3)
6.40E+00	5.80E-01	6.60E+58

SNR	Model Type	Age(yrs)	Energy(ergs)	q =Mdot/4 pi Vw)	RS Radius(pc)	RS Temp.(keV)	RS Emission Measure(cm^-3)
E0102/J0104-7201	s=2,n=7,5Msun	3.87E+02	1.58E+52	5.99E+13	4.78E+00	4.94E-01	3.18E+58
	s=2,n=10,5Msun	6.83E+02	4.66E+51	7.54E+13	5.08E+00	9.99E-02	4.12E+59
	s=2,n=14,5Msun	5.81E+02	5.15E+51	6.52E+13	5.20E+00	5.17E-02	1.41E+60
	s=2,n=7,10Msun	3.87E+02	2.23E+52	5.99E+13	4.78E+00	4.94E-01	3.18E+58
	s=2,n=10,10Msun	6.83E+02	7.65E+51	7.54E+13	5.08E+00	9.98E-02	4.12E+59
	s=2,n=14,10Msun	5.81E+02	9.07E+51	6.52E+13	5.20E+00	5.17E-02	1.41E+60
	s=2,n=7,20Msun	3.87E+02	3.16E+52	5.99E+13	4.78E+00	4.94E-01	3.18E+58
	s=2,n=10,20Msun	6.83E+02	1.26E+52	7.54E+13	5.08E+00	9.98E-02	4.12E+59
	s=2,n=14,20Msun	5.81E+02	1.60E+52	6.52E+13	5.20E+00	5.17E-02	1.41E+60
	s=2,n=7,40Msun	3.87E+02	4.46E+52	5.99E+13	4.78E+00	4.94E-01	3.18E+58
	s=2,n=10,40Msun	6.83E+02	2.06E+52	7.54E+13	5.08E+00	9.98E-02	4.12E+59
	s=2,n=14,40Msun	5.81E+02	2.82E+52	6.52E+13	5.20E+00	5.17E-02	1.41E+60

A comparison of the model RS EM with the observed one (5.6e59) shows that something intermediate between n=10 and n=14 is preferred, e.g n=12 would reproduce the RS EM well. The RS q, RS EM, RS temperature and RS radius depend on n but are independent of the ejecta mass. Only the explosion energy increases with ejecta mass. The observations do not very well constrain the explosion energy. A measurement of the RS radius would help constrain the models. From the X-ray image of Alan et al (2019) the outer edge of the interior bright ring yields a RS radius of approximately 4.5 pc which is more consistent with the n=7 model than the n=10 or n=14 models. The difficulty of matching RS radius, temperature and emission measure with a single n value may indicate that the ejecta density profile is not well represented by a power law or that deviations from spherical symmetry are important.

J0049-7314

FS Radius(pc)	FS Temp.(keV)	FS EM (cm^-3)
2.77E+01	5.20E-01	3.16E+58

SNR	Model Type	Age(yrs)	Energy(ergs)	q or Density(cm^-3)	RS Radius(pc)	RS Temp.(keV)	RS EM (cm^-3)	RS Reaches Core(yrs)	RS Reaches Center(yrs)
J0049-7314Ia	s=2,n=7,1.4Msun	1.63E+03	2.17E+52	8.62E+13	2.07E+01	4.43E-01	1.52E+58	N/A	N/A
J0049-7314Ia	s=2,n=10,1.4Msun	2.71E+03	3.77E+51	1.08E+14	2.20E+01	8.95E-02	1.97E+59	N/A	N/A
J0049-7314Ia	s=2,n=14,1.4Msun	2.37E+03	2.84E+51	9.38E+13	2.25E+01	4.64E-02	6.75E+59	N/A	N/A
J0049-7314Ia	s=0,n=7,1.4Msun	1.81E+04	1.16E+51	7.24E-02	0.00E+00	3.08E+00	1.64E+55	4.58E+02	3.40E+03
J0049-7314Ia	s=0,n=10,1.4Msun	1.80E+04	1.17E+51	7.24E-02	0.00E+00	1.90E+00	2.81E+55	2.76E+02	3.43E+03
J0049-7314Ia	s=0,n=14,1.4Msun	1.80E+04	1.17E+51	7.25E-02	0.00E+00	1.34E+00	4.05E+55	1.97E+02	3.60E+03

J0049-7314 is a type Ia SNR. s=2 models yield a lower age (1600-2700 yr) vs s=0 models (~18000yr). The energy is higher for the s=2 models (2-20 FOE, vs 1 FOE for s=0 models). The measured RS EM is ~7e58 cm^{-3} which is consistent with s=2 and n=8 or 9. Thus we conclude this SNR likely exploded in a stellar wind cavity with q~1e14 gm/cm.

J0051-7321

FS Radius(pc)	FS Temp.(keV)	FS EM (cm^-3)
2.11E+01	2.10E-01	1.71E+60

SNR	Model Type	Age(yrs)	Energy(ergs)	q or Density(cm^-3)	RS Radius(pc)	RS Temp.(keV)	RS EM (cm^-3)	RS Reaches Core(yrs)	RS Reaches Center(yrs)
J0051-7321CC	s=2,n=7,5Msun	3.91E+03	9.27E+51	5.54E+14	1.58E+01	1.79E-01	8.24E+59	N/A	N/A
	s=2,n=10,5Msun	7.76E+03	1.04E+51	6.97E+14	1.68E+01	3.62E-02	1.07E+61	N/A	N/A
	s=2,n=14,5Msun	6.51E+03	8.29E+50	6.03E+14	1.71E+01	1.87E-02	3.65E+61	N/A	N/A
	s=0,n=7,5Msun	2.23E+04	2.14E+51	7.94E-01	0.00E+00	1.48E+00	5.36E+56	4.38E+02	3.24E+03
	s=0,n=10,5Msun	2.21E+04	2.19E+51	7.94E-01	0.00E+00	9.22E-01	9.18E+56	2.63E+02	3.27E+03
	s=0,n=14,5Msun	2.21E+04	2.18E+51	7.95E-01	0.00E+00	6.49E-01	1.32E+57	1.87E+02	3.42E+03

J0051-7321 is a CC-type SNR. s=2 models yield a lower age (4000-8000 yr) than s=0 models (~22000yr). The energy for the s=0 models is ~2 FOE, whereas the s=2 models can have a wide rang (1-9 FOE). The measured RS EM is ~1.2e59 cm^{-3} which is closer to the s=2 values but with n<7. We conclude this SNR likely exploded in a stellar wind cavity with q~3e14 gm/cm.

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ANALYSIS

We consider the SNRs in the SMC that have measured X-ray spectra (19 from Maggi+ 2019 and one (1E 0102.2-7219) from Allen+ 2019).

The forward shock properties of these 20 SNRs were considered by Leahy & Filipovic (2022) with results given in their Table 1, using the model for SN evolution in a uniform ISM (s=0) and with ejecta density power-law index of n=7. The uncertainties calculated by running a series of models for the upper and lower limits of the input parameters. The 6 SNRs of interest (outlined in red below) have detected reverse shock (RS) emission.

Table 1
All SNRs: Standard ($s = 0$, $n = 7$ Forward Shock) Model Results

SNR	SN type	M_{ej} ($M_\odot$)	Age(+. −) (kyr)	Energy(+, −) (10^{50} erg)	Density(+, −) (10^{-2} cm^{-3})
J0041-7336	CC	5	19.4(+2.6, −1.6)	23.6(+4.4, −5.3)	6.1(+0.7, −0.3)
J0046-7308	CC	5	14.5(+1.7, −1.4)	16.3(+3.5, −3.3)	14.6(+3.0, −1.7)
J0047-7308	CC	5	9.7(+0.5, −0.3)	11.2(+1.8, −1.0)	36.6(+6.1, −0.6)
J0047-7309	CC	5	12.9(+1.8, −2.5)	13.0(+6.8, −7.2)	14.2(+5.3, −8.7)
J0048-7319	unknown	1.4	8.0(+1.3, −3.2)	14.2(+24.9, −3.8)	6.1(+1.7, −2.1)
J0049-7314	Ia?	1.4	18.1(+3.5, −2.6)	11.5(+4.7, −3.4)	7.3(+3.3, −2.2)
J0051-7321	CC	5	22.3(+0.6, −0.5)	21.4(+1.3, −2.1)	79.6(+4.9, −8.1)
J0052-7236	CC	5	34.5(+10.9, −14.8)	46.7(+114.0, −30.8)	10.5(+25.5 , −7.1)
J0056-7209	unknown	1.4	20.6(+19.0, −10.6)	22.4(+71.7, −16.3)	2.8(+2.6, −0.9)
J0057-7211	unknown	1.4	10.3(+2.6, −2.9)	12.3(+11.5, −4.5)	5.5(+0.7, −0.8)
J0058-7217	CC	5	29.6(+4.4, −7.1)	36.2(+27.0, −18.4)	13.9(+10.4, −7.2)
J0059-7210	CC	5	12.1(+0.3, −0.3)	25.9(+1.3, −1.2)	33.1(+1.5, −1.4)
J0100-7133	CC	5	20.9(+5.1, −3.0)	13.1(+7.0, −4.6)	6.4(+3.8, −1.1)
J0103-7209	CC	5	15.6(+3.1, −3.6)	43.3(+30.4, −13.0)	3.4(+0.4, −0.4)
J0103-7247	CC	5	5.1(+0.4, −0.3)	8.7(+1.4, −1.4)	10.6(+2.6, −2.4)
J0104-7201[a]	CC	5	4.2(+0.1, −0.3)	7.2(+1.2, −0.8)	338(+43, −40)
J0105-7210	Ia?	1.4	12.4(+1.4, −0.2)	13.1(+2.0, −2.5)	12.2(+2.1, −1.1)
J0105-7223	CC	5	30.8(+0.8, −0.8)	47.0(+2.6, −2.8)	83.0(+4.6, −4.8)
J0106-7205	Ia?	1.4	7.7(+0.5, −0.4)	9.8(+1.1, −1.2)	37.5(+2.8, −3.0)
J0127-7333	unknown	1.4	26.7(+0.7, −1.3)	9.1(+2.9, −2.6)	25.0(+7.8, −7.1)

The 6 SNRs with observed RS emission have their X-ray spectrum properties for forward and reverse shock components listed in the Table below. The abundances are given relative to solar abundance values.

MCSNR	type	Rav(pc)	kT (keV)	kT+	kT-	EM (1e58/cm^3)	EM+	EM-	CSM Abundances	kT2 (keV)	kT2+	kT2-	EM2 (1e58/cm^3)	EM2+	EM2-	RS Abundances
		FS properties								RS properties						
J0049-7314	Ia	27.65	0.52	0.67	0.38	3.16	6.79	1.52	RD92	0.91	0.94	0.88	7.28	8.53	6.29	pure Fe
J0051-7321	CC	21.1	0.21	0.22	0.2	171	193.4	137.4	RD92	0.73	0.89	0.62	12.4	17.66	10.25	Ne1.74, Mg0.93, Si2.13
J0104-7201	CC	6.4	0.58	0.68	0.56	3.009	3.538	2.562	O0.11,Ne0.13,Mg0.08,Si0.13,Fe0.04	0.77	1.08	0.62	33.2	35.8	31.1	O0.87,Ne1.63,Mg0.68,Si0.15
J0105-7223	CC	27.95	0.19	0.2	0.18	448	499.7	396.3	RD92	0.38	0.39	0.37	85.3	109	64.6	O1.23,Ne1.64,Mg0.94,Fe0.13
J0105-7210	Ia	21.95	0.68	0.88	0.57	4.44	6.16	3.66	RD92	0.78	0.85	68	1.88	2.51	1.3	pure Fe
J0106-7205	Ia	13.65	0.72	0.79	0.64	9.95	11.54	8.44	RD92	1	1.03	0.97	7.88	8.91	6.93	pure Fe

J0105-7210

FS Radius(pc)	FS Temp.(keV)	FS EM (cm^-3)
2.80E+01	6.80E-01	4.44E+58

User Defined Label	Model Type	Age(yrs)	Energy(ergs)	ISM # Density(cm^-3)	RS Radius(pc)	RS Temp.(keV)	RS EM(cm^-3)	RS Reaches Core(yrs)	RS Reaches Center(yrs)
J0105-7210Ia	s=2,n=7,1.4Msun	1.41E+03	3.27E+52	1.03E+14	2.09E+01	7.09E-01	1.44E+58	N/A	N/A
J0105-7210Ia	s=2,n=10,1.4Msun	2.29E+03	5.68E+51	1.29E+14	2.22E+01	1.43E-01	1.87E+59	N/A	N/A
J0105-7210Ia	s=2,n=14,1.4Msun	2.03E+03	4.12E+51	1.12E+14	2.27E+01	7.42E-02	6.40E+59	N/A	N/A
J0105-7210Ia	s=0,n=7,1.4Msun	1.57E+04	1.88E+51	8.41E-02	0.00E+00	5.24E+00	1.16E+55	3.42E+02	2.53E+03
J0105-7210Ia	s=0,n=10,1.4Msun	1.55E+04	1.92E+51	8.42E-02	0.00E+00	3.25E+00	1.98E+55	2.05E+02	2.55E+03
J0105-7210Ia	s=0,n=14,1.4Msun	1.56E+04	1.91E+51	8.42E-02	0.00E+00	2.29E+00	2.85E+55	1.46E+02	2.67E+03

J0105-7210 is a type Ia SNR. s=2 models yield a lower age (1400-2300 yr) vs s=0 models (~16000yr). The energy for the s=0 models is ~2 FOE, whereas the s=2 models are much higher energy (4-30 FOE). The measured RS EM is ~2e58 cm^{-3} which is close to the s=2 model with n=7. We conclude this SNR is likely a high energy explosion in a stellar wind cavity with q~1e14 gm/cm.

J0105-7223

FS Radius(pc)	FS Temp.(keV)	FS EM (cm^-3)
2.80E+01	1.90E-01	4.48E+60

User Defined Label	Model Type	Age(yrs)	Energy(ergs)	ISM # Density(cm^-3)	RS Radius(pc)	RS Temp.(keV)	RS EM(cm^-3)	RS Reaches Core(yrs)	RS Reaches Center(yrs)
J0105-7223CC	s=2,n=7,5Msun	6.26E+03	9.95E+51	1.03E+15	2.09E+01	1.62E-01	2.16E+60	N/A	N/A
	s=2,n=10,5Msun	1.18E+04	1.03E+51	1.30E+15	2.22E+01	3.27E-02	2.80E+61	N/A	N/A
	s=2,n=14,5Msun	1.01E+04	7.11E+50	1.12E+15	2.27E+01	1.70E-02	9.57E+61	N/A	N/A
	s=0,n=7,5Msun	3.09E+04	4.71E+51	8.27E-01	0.00E+00	2.27E+00	3.33E+56	2.91E+02	2.16E+03
	s=0,n=10,5Msun	3.06E+04	4.81E+51	8.30E-01	0.00E+00	1.41E+00	5.67E+56	1.75E+02	2.17E+03
	s=0,n=14,5Msun	3.07E+04	4.78E+51	8.28E-01	0.00E+00	9.98E-01	8.09E+56	1.25E+02	2.28E+03

J0105-7223 is a CC-type SNR. s=2 models yield a lower age (6000-12000 yr) than s=0 models (~31000yr). The energy for the s=0 models is ~5 FOE, whereas for the s=2 models there is a range of energy (1-10 FOE). The measured RS EM is large: ~8.5e59 cm^{-3} which is closer to the s=2 model with n less than 7. We conclude this SNR is likely a high energy explosion in a stellar wind cavity with q~1e15 gm/cm.

J0106-7205

FS Radius(pc)	FS Temp.(keV)	FS EM (cm^-3)
1.37E+01	7.90E-01	9.95E+58

User Defined Label	Model Type	Age(yrs)	Energy(ergs)	ISM # Density(cm^-3)	RS Radius(pc)	RS Temp.(keV)	RS EM(cm^-3)	RS Reaches Core(yrs)	RS Reaches Center(yrs)
J0106-7205Ia	s=2,n=7,1.4Msun	6.59E+02	2.56E+52	1.07E+14	1.02E+01	6.73E-01	4.79E+58	N/A	N/A
	s=2,n=10,1.4Msur	1.10E+03	4.86E+51	1.35E+14	1.08E+01	1.36E-01	6.21E+59	N/A	N/A
	s=2,n=14,1.4Msur	9.59E+02	3.87E+51	1.17E+14	1.11E+01	7.05E-02	2.12E+60	N/A	N/A
	s=0,n=7,1.4Msun	7.31E+03	1.09E+51	3.74E-01	0.00E+00	3.58E+00	1.11E+56	2.72E+02	2.02E+03
	s=0,n=10,1.4Msur	7.27E+03	1.10E+51	3.74E-01	0.00E+00	2.19E+00	1.91E+56	1.65E+02	2.05E+03
	s=0,n=14,1.4Msur	7.29E+03	1.09E+51	3.75E-01	0.00E+00	1.53E+00	2.77E+56	1.18E+02	2.15E+03

J0106-7205 is a type Ia SNR. s=2 models yield a lower age (600-1100 yr) vs s=0 models (~7000yr). The energy for the s=0 models is ~1 FOE, whereas the s=2 models have a range of energy (4-25 FOE). The measured RS EM is large: ~8e58 cm^{-3} which is closer to the s=2 model with n ~8. We conclude this SNR is likely a high energy explosion in a stellar wind cavity with q~1e14 gm/cm.

Discussion

Here we have carried out a study of the 6 SNRs in the Small Magellanic Cloud (SMC) that have measured reverse shock (RS) emission in addition to the (normally) detected forward shock emission. There are 3 CC-type SNRs and 3 type Ia SNRs in this sample. All of the SNRs have a large emission measure (EM) for the reverse shock, in part because a large reverse shock EM is needed in order for detection at distances as large as the SMC (60 kpc), Thus we are sampling the SNRS with the brightest RS emission in the SMC. All of the SNRs are fit much better with explosions in a stellar wind cavity than explosions in a uniform ISM. This is likely an observational selection effect, because the RS emission is much brighter for "wind explosions" than "ISM explosions" (Leahy et al, 2019).

The CC-type SNRs (J0051-7321, J0104-7219 and J0105-7223) have estimated explosion energies of ~5,10 and 5 FOE and stellar wind parameters, q, of 6e14, 6e13 and 1e15 resp. Interestingly the q values are better constrained than the energies. For a typical massive stellar wind velocity of 300 km/s the mass loss rates are ~4e-4, 4e-3 and 6e-3 Msun/yr, resp., for these 3 SNRs, which are very high mass loss rates, and may indicate LBV progenitors.

The type Ia SNRs (J0049-7314, J0105-7210 and J0106-7205) have estimated explosion energies of ~5,10 and 5 FOE and stellar wind parameters, q, of 1e14, 6e13 and 1e14 resp. For a typical low-mass stellar wind velocity of 20 km/s q or Density(cm^-3) the mass loss rates are ~4e-5 Msun/yr for these 3 SNRs, which are high mass loss rates for a low mass star, and more characteristic of the late AGB phase. This may not be a coincident because although the late AGB phase is short, the high mass loss rate make explosion of a white dwarf companion more likely.

CONCLUSIONS and FUTURE WORK

This study of the 6 SNRs in the Small Magellanic Cloud that have reverse shock emission has shown some interesting results. All SNRs are consistent with explosion in a stellar wind cavity, which may be partly a selection effect, because such explosions have bright reverse shock emission. Both CC-type and type Ia SNRs are stellar wind explosions. The mass loss rates for the CC-type explosions are very high (10^{-4} to 10^{-3} Msun/yr) which may point to progenitors are LBV stars, which can have such high mass loss rates. The type Ia SNRs have lower mass loss rates (~4x10^{-5} Msun/yr), which are high for low mass companions, unless they are in the AGB phase of evolution.
Future work will extend the study to other SNRs with detected reverse shock emission, in order to learn more about the circumstellar environments of SNRs, explosion energies and ejecta density profiles.