Supernova Remnants Interacting with Circumstellar Medium

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Circumstellar Nebulae Created by Stellar Winds

- Mass loss is a key phenomenon in a massive stars' evolution.
- Latest mass losses form circumstellar nebulae that
 - 1) affect SN subtypes
 - 2) allow us to study the nature of progenitor stars.
 - η Carina a LBV star



Homunculus nebula created by the great eruptions ($M_{ej} > 10 M_{\odot}$) around 1843

Outer shell by eruptions ~1000 yr ago



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SNRs Offer the Best Laboratories to Study the Latest Stellar Winds (CS Nebulae)

Monitoring observations of SNe allow us to study the history of mass losses.



11/2000 1/2003 9/2005 12/2006 4/2009 1/2011 2/2013 6/2014 12/2000 03/2011 12/2002 01/2005 01/2007 01/2009 03/2013 09/2014 (5.036 davs) (5.789 days) (6.529 davs) (7,270 days) (8.000 davs) (8,796 days) (9,523 days) (10,071 days) 2000.9 2011.3

At t = 1 yr, the SN shock reaches a wind blown 10^2-10^3 yr before explosion. At t = 10 yr, the SN shock reaches a wind blown 10^3-10^4 yr before explosion. (assuming V_{wind} = 10^{1-2} km/s, V_{shock} = 10^4 km/s)

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Evolution of SN 1987A

Talk Plan

- Very young extragalactic SNe/SNRs (1–30 yr)
- Young Galactic SNRs (300—3000 yr)
- Evolved SNRs (~10000 yr)

I will mainly focus on X-ray observations of these objects.



SN 2005ip in NGC 2906 @ 30 Mpc

What Can We Learn from X-Ray Obs.?



Stellar Wind Properties \rightarrow Progenitors



CSM Geometry from X-Ray Evolution



Similar X-Ray Spectral Evolution for Type IIn SNe 2005kd and 2006jd



SK et al. 2016

Diversity of X-Ray Spectral Evolution

Another SNe IIn 2005ip does not exhibit the characteristic three-phase spectral evolution. Its X-ray spectrum smoothly softens with time.

This evolution can be explained if the CSM torus is viewed edge-on.



CSM Geometry Inferred from Optical Spectropolarimetry

Spectropolarimetry allows us to probe geometries of ejecta and CSM.



Disk-like CSM is roughly consistent with our inference from X-ray observations.

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- Evolved SNRs (~10000 yr) SN 1604 (Kepler's SNR)



Cassiopeia A: QSFs

Quasi-stationary flocculi (QSFs)



Line intensities of QSFs and some models

	Observed Intensities: $A_v = 4.3$		RAYMOND MODEL I	RAYMOND MODEL 7:	Observed Intensities: 4 = 65	RAYMOND MODEL A	
Line	1Q1	2Q4	$v_{s} = 60 \text{ km s}^{-1}$	$v_s = 60 \text{ km s}^{-1}$	1Q1	$v_s = 50 \text{ km s}^{-1}$	
β λ4861	100	< 180	100	100	100	100	
π λ4959	< 62	< 137	11.7	11.4	< 58	1.36	
π λ5007	50	< 120	34.6	33.9	46	4.03	
π λ5159	30	< 90	2110	0000	26		
1 35198]	50		(2.98	2 01)	20	3.66	
1 λ5200	32	< 84	12.98	1 33	27	3.99	
μ λ5527	20	< 52	(2.50	1.55)	14		
π λ5755	109	64	3.18	4.16	70	7.73	
e 1 λ5876	62	88	5.93	5.43	37	9.84	
1 λ6300	170	< 26	22.5	48.6	84	22.2	
Ι λ6364	56	< 26	7.25	15.7	27	7.15	
Π λ6548	559	676	46.5	56	254	78	
α λ6562	676	676	509	505	300	317	
Π λ6583	1710	2030	140	168	760	233	
e 1 λ6678	10	< 26	1.7	1.5	4	2.8	
π λ6716	12	< 26	48.2	27.5	5	90.6	
Π λ6731	32	< 26	36.0	43.3	13	66.2	
e I λ7065	10	< 33	0.48	0.44	4	0.79	
επ λ7155	25	< 35			ġ		
апλ7291		< 37	1.72	2.54		3.12	
Π λ7320-30]			(15.4	36.5		[41.6	
апλ7324 }·····	62	< 37	1.14	1.70	21	2.08	

\rightarrow N and He rich

(Kirshner & Chevalier 1977; Chevalier & Kirshner 1978)

V <~ 500 km/s (Kamper & van den Bergh 1976)

Kinematic properties and [NII]/H α ratios resemble WR nebula NGC 6888 (Kirshner & Chevalier 1977).



Cassiopeia A: FMFs

Fast-moving flocculi (FMFs) v ~ 5000 km/s



Similar abundance pattern to QSFs



N- and He-rich surface at the time of explosion → Progenitor was a late WN star (WN7—WN9), not WC nor WO

G292.0+1.8: CSM Ring



See also Park et al. 2002; 2004; 2007; Lee et al. 2009; Ghavamian et al. 2012

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G292.0+1.8: Ambient Density Structure



- The total mass of the CSM: ~14 M_{\odot} (Bhalerao+ 2019)

RCW 89 (+ MSH 15-52)



RCW 89 Optical spectroscopy: N/O ~ 5 solar S/O ~ 1 solar (Dopita et al. 1977)

SN Type: Ib/c from a large E/M ratio (Gaensler+99; Chevalier 05)

→ RCW 89 may be a RSG wind swept up by WR winds

High-Res. X-Ray Spectroscopy of RCW 89



SK, Yatsu et al. in preparation

- Solar abundance (but N lines not detected)
- Doppler velocity ~ 400 km/s
- \rightarrow Not SN ejecta, but it's unclear if it's RSG wind.

RX J1713.7-3946: A Thermal Clump



It was previously thought to be a WR 85 (Pfeffermann & Aschenbach 1996). But, it turned out to be displaced ~0.3 pc from WR 85 (too far to be related)!

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X-Ray Spectrum of the Thermal Clump



RCW 103 & Puppis A

RCW 103 (~2000 yrs old)



Optical studies:

- Slight N enhancement (N/H ~ 2 solar)
- H₂ shell (→ swept up by stellar wind?)
 (e.g., Meaburn & Allan1983; Oliva+1990)

Puppis A (~4500 yrs old)



Optical studies:

- Strong N enhancement (N/H ~ 10 solar)
- Both slow-moving and fast-moving (Dopita+77; Winkler+89; P. Ghavamian's talk)
- ightarrow Similar to Cas A

Kepler's SNR: Type Ia with CSM



Optical & IR observations

Dense (n ~ 100 cm⁻³) N-rich (N/H ~ 4 times solar) knots (e.g., Blair et al. 1991; 2007; Williams et al. 2012)

\rightarrow CSM from a progenitor system.

Chiotellis et al. (2012) specified the progenitor mass to be 5 M_{\odot} (\rightarrow AGB star), based on the N abundance.

	Pr	oduction factor	Wind's abundances:			
	F = lo	$g[\langle X_{i,\text{final}} \rangle / \langle X_{i,\text{in}} \rangle$	$[X_i]/[X_{i,\odot}]$			
	¹² C	¹⁶ O	¹⁴ N	¹² C	16O	¹⁴ N
$4 M_{\odot}$	0.33	-2.6×10^{-2}	0.42	2.1	0.9	2.6
$5 M_{\odot}$	0.14	-4.3×10^{-2}	0.61	1.4	1.0	4.1
$6 M_{\odot}$	-0.22	-8.1×10^{-2}	0.91	0.6	0.8	8.1

X-Ray Evidence for Diffuse N-rich CSM



Was Kepler's SN an Overluminous Ia?



Was Kepler's SN "la-CSM" with Extremely-Late Interaction with a CSM?

Kepler's SN

- 1) Is associated with CSM (interactions started ~300 yr after the SN)
- 2) Was possibly an overluminous Ia (91T-like)
- \rightarrow Consistent with "Ia-CSM".



This result supports the recent argument by Leloudas et al. (2015) that overluminous Ia and Ia-CSM are fundamentally the same objects.

N103B: Old Cousin of Kepler' SNR

Williams et al. (2014)



- Dense (~45 cm⁻³) gas in the west
- Bow-shock shape assures the optical emission is part of N103B.
- → CSM from a relatively young and massive progenitor, not an AGB or RGB, because there is no evidence for N enhancements.

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Recombining Plasmas in SNRs: A New Clue to Progenitors



Possible Formation Processes of RPs



Images taken from Okon-san's master thesis (Kyoto U.)

How to Distinguish the Two Scenarios

Observational signatures

Adiabatic cooling Positive correlation between T_e and n_e (Low ISM density \rightarrow low T_e) <u>Thermal conduction cooling</u> Anti-correlation between T_e and n_e (High ISM density \rightarrow low T_e)



For W49B, there is a positive correlation between T_e and n_e , favoring the adiabatic cooling as the origin of the recombining plasma.

Object	VEM	Radius / Distance	Age (yr)	MC association	Origin	Reference	Mass (f ^{0.5} M _●)
G359.1- 0.5	7.2e11*4*3.14*D **2=6.3e57	12' / 8.5 kpc (r=30 pc)	7e4	Yes	Ad. cooling	Ohnishi+2011	89
G346.6- 0.2	40e57	4' / 8 kpc (r=9 pc)	1.5e4	Yes	?	Yamauchi+2013	39
W28	40e57	24' / 2 kpc (r=14 pc)	3.5e4	Yes	Th. cond.	Okon+2018	72
W44	980e57	18' / 3 kpc (r=16 pc)	2e4	Yes	Ad. cooling	Uchida+2012	430
CTB 37A	89e57	1.1e59cm3 (7.5' / 10kpc) (r=22 pc)	2e4	Yes	?	Yamauchi+2014	61
3C391	1.8e59	3' / 8 kpc (r=7pc)	2e4	Yes	Ad. cooling	Sato+2014	54 (10-25)
MSH 11- 61A	23e11*4*3.14*D **2=13.6e57	2.5' / 7 kpc (r ~ 15 pc)	1.5e4	Possible	Ad. cooling	Kamitsukasa+2015	9.3
N49	17e57	0.6' / 50 kpc (r=8.7 pc)	5000	Yes	?	Uchida+2015	23
IC443	30e57	22' / 1.5 kpc (r=9.6 pc)	3e4	Yes	Th. cond.	Matsumura+2018	36
W49B	81e11*4*3.14*D **2=63e57	2' / 8 kpc (r=4.7 pc)	5000	Yes	Ad. cooling	Ozawa+2009	17
G166.0+ 4.3	1e58	10' / 5 kpc (r=14.5 pc)	4e4	Possible	?	Matsumura+2017	38
N132D	1.3e12*4*3.14*D **2=390e57	0.5' / 50 kpc (r=7.3 pc)	2500	Yes	?	Bamba+2018	85
Kes17	34e11*4*3.14*D **2=92e57	4' / 15 kpc (r=17.4 pc)	2e4	Yes	Th. cooling	Washino+2016	153
3C400.2	0.21e57	15' / 2.8 kpc (r=12.2 pc)	2e4	Yes	Ad. cooling	Ergin+2016	14
CTB1	9.5e12*4*3.14*D **2=4.6e57	17' / 2 kpc (r=9.9 pc)	1.6e4	No (Not yet?)	Th. cooling	Katsuragawa+2018	15

Summary

- Supernova ejecta will first interact with the circumstellar medium created by stellar winds from a progenitor star.
 Emission from the SN-CSM interaction is an important clue to probing the CSM and the nature of the progenitor stars.
- <u>For extragalactic SNe</u>, X-ray observations of allow us to study mass-loss rates and CSM geometries.
- <u>For young SNRs</u>, detailed studies of CSM knots allow us to assess the nature of progenitor stars.
- <u>For evolved SNRs</u>, recombining plasmas may be the signature of the presence of massive CSM around the progenitor stars.

Implications for Progenitors in Ad. Cooling

The adiabatic cooling scenario provides evidence for a CSM from a progenitor. Moriya (2012) examined conditions for RPs to be present for various progenitors.



 \rightarrow The progenitors of RP SNRs may be RSG stars.

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Comparison with Stellar Wind's Spectra

(A) SN 1987A ring



Sturm et al. (2010) $\int_{0}^{1} \frac{1}{2} \frac{1}{$

(B) WC-type WR (θ Muscae)



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C lines (no N)

(C) WN-type WR (WR6)

A single WR star



© someinterestingfacts



N lines (no C, O)

best matches the thermal clump! \rightarrow RSG wind?

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Size and Mass of the CSM Torus

- The size of the CSM torus: ~5x10¹⁶ cm (V_{sh} / 8000 km s⁻¹) (t / 2yr)
- The mass of the CSM torus: X-ray light curves → M_{dot} ~ 0.01 (V_w / 100 km s⁻¹) M_☉
 → M ~ 5 M_☉ in the torus.

The CSM rings of SN 1987A



The CSM properties in SNe IIn are very different from those of SN 1987A, suggesting a different nature of the progenitor.