PROGENITORS OF RECOMBINING SUPERNOVA REMNANTS

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ABSTRACT

Usual supernova remnants have either ionizing plasma or plasma in collisional ionization equilibrium, i.e., the ionization temperature is lower than or equal to the electron temperature. However, the existence of recombining supernova remnants, i.e., supernova remnants with ionization temperature higher than the electron temperature, has been recently confirmed. One suggested way to have recombining plasma in a supernova remnant is to have a dense circumstellar medium at the time of the supernova explosion. If the circumstellar medium is dense enough, collisional ionization equilibrium can be established in the early stage of the evolution of the supernova remnant and subsequent adiabatic cooling, which occurs after the shock wave gets out of the dense circumstellar medium, makes the electron temperature lower than the ionization temperature. We study the circumstellar medium around several supernova progenitors and show which supernova progenitors can have a circumstellar medium dense enough to establish collisional ionization equilibrium soon after the explosion. We find that the circumstellar medium around red supergiants (especially massive ones) and the circumstellar medium dense enough to make Type IIn supernovae can establish collisional ionization equilibrium soon after the explosion and can evolve to become recombining supernova remnants. Wolf–Rayet stars and white dwarfs have the possibility to be recombining supernova remnants but the fraction is expected to be very small. As the occurrence rate of the explosions of red supergiants is much higher than that of Type IIn supernovae, the major progenitors of recombining supernova remnants are likely to be red supergiants.

Key words: ISM: supernova remnants – supernovae: general

Online-only material: color figures

1. INTRODUCTION

X-ray observations by the Suzaku satellite have confirmed the existence of recombining supernova remnants (SNRs; Yamaguchi et al. 2009, 2012; Ozawa et al. 2009; Ohnishi et al. 2011; Sawada & Koyama 2012). Recombining SNRs are SNRs in which the ionization temperature is higher than the electron temperature. The forward shock wave that emerged at the time of a supernova (SN) explosion propagates in the interstellar medium (ISM). As the typical density of the ISM is very small (n_e ≈ 1 cm^{-3} or less, where n_e is the electron number density), the timescale to reach collisional ionization equilibrium (CIE) in the shocked ISM is typically ∼10^7 years or longer (e.g., Masai 1984). Electrons heated by Coulomb interaction with ions in the shocked ISM collisionally excite ions and reach CIE with this timescale. Thus, young SNRs before CIE are supposed to be ionizing SNRs in which the electron temperature is higher than the ionization temperature and evolve to SNRs in CIE. Most SNRs are known to be in either the ionizing stage or CIE (e.g., Kawasaki et al. 2005). In this simple picture, SNRs cannot be recombining SNRs and the confirmation of recombining SNRs challenges the current understanding of the evolution of SNRs.

There are several suggested mechanisms for creating recombining plasma in SNRs (see, e.g., Yamaguchi et al. 2012 and references therein). The existence of a dense circumstellar medium (CSM) is one possible way to explain recombining SNRs (e.g., Itoh & Masai 1989; Shimizu et al. 2012; Zhou et al. 2011). If a dense CSM is around an SN, CIE can be achieved in much shorter timescales (∼10^4/(n_e/1 cm^{-3}) years). When the shock wave reaches the outer edge of the dense CSM, the shocked CSM suddenly expands adiabatically and the electron temperature suddenly decreases and the plasma starts to recombine.

Although the existence of the dense CSM at the time of the SN explosion has been suggested as a possible mechanism to realize recombining SNRs, we still do not have a clear picture about possible SN progenitors that can have a CSM dense enough to make recombining SNRs. In this Letter, we look into the properties of the CSM around SN progenitors at the time of SN explosions and investigate the progenitors that can evolve to become recombining SNRs. We focus on massive star progenitors because two recombining SNRs, IC 443 and W49B, are clearly associated with massive star-forming regions (e.g., Yamaguchi et al. 2012) but we also investigate possible channels for white dwarfs to become recombining SNRs.

2. POSSIBLE PROGENITORS

2.1. Red Supergiants and Wolf–Rayet Stars

Red supergiants (RSGs) and Wolf–Rayet (W–R) stars are progenitors of core-collapse SNe. Because of their high luminosities, they lose their mass before they explode. Thus, RSGs and W–R stars explode inside the CSM created by the preceding stellar evolution. If we assume that the CSM is from a steady wind with velocity v_w and mass-loss rate M, the wind density ρ_w becomes

\[
\rho_w = \frac{M}{4\pi r^2 v_w},
\]

where r is the radius.

If the star inside the CSM explodes, a forward shock propagates in the CSM. Assuming that the adiabatic index of the
system is three-fifths, the density $\rho_s$ of the shocked CSM just behind the forward shock becomes $\rho_s = 4\rho_w$. As the forward shock propagates in the CSM, it decelerates, especially if the CSM is dense. However, the mass of the CSM swept up by the forward shock is still small compared to the progenitor mass in the early epochs we are interested in, and we assume that it is freely expanding with velocity $v_\text{e}$ for simplicity. Note that the deceleration makes the time of the interaction between the shock wave and the CSM longer and thus CIE can be achieved easier with the deceleration. The typical $v_\text{e}$ of standard SN explosions is $v_\text{e} \sim 10,000 \text{ km s}^{-1}$ (e.g., Suzuki & Nomoto 1995; Fransson et al. 1996; Dwarkadas 2005, 2007). The location of the forward shock at time $t$ after the explosion is $r = v_\text{e} t$ and $\rho_s$ can be expressed as

$$\rho_s = \frac{M}{\pi v_\text{e}^2 t^2 v_\text{w}}.$$  \hspace{1cm} (2)

Although Equation (2) describes the evolution of the density just behind the shock, the remaining entire shocked CSM has similar densities when the shock is traveling in the density structure close to $\rho_w \propto r^{-2}$ (see, e.g., Chevalier 1982; Suzuki & Nomoto 1995; Fransson et al. 1996; Dwarkadas 2005, 2007) and we assume that $\rho_s$ is a typical value in the shocked CSM. The actual densities in the shocked CSM are slightly higher than $\rho_s$.

Since the wind properties of RSGs and W-R stars differ, we consider the two cases separately.

### 2.1.1. Red Supergiants

The typical mass-loss rate and wind velocity of RSGs are $\sim 10^{-5} M_{\odot} \text{ yr}^{-1}$ and $\sim 10 \text{ km s}^{-1}$, respectively (e.g., Mauron & Josselin 2011), and they are consistent with those estimated from the observations of SN explosions from RSGs (Type IIP SNe; e.g., Chevalier et al. 2006). If we assume that the RSG wind has solar metallicity and H and He in the wind are fully ionized when the forward shock passes, $\rho_s = 2.0 \times 10^{-24} n_{\text{e}}$, where $n_{\text{e}}$ is the electron number density in the shocked CSM. From Equation (2), the time evolution of $n_{\text{e}}$ is

$$n_{\text{e}} t^2 = \frac{4}{\pi} M_s v_\text{w}^3 v_\text{w}^{-1} \text{ cm}^3 \text{ s}^2,$$  \hspace{1cm} (3)

where $M_s$ is $M$ scaled by $10^{-5} M_{\odot} \text{ yr}^{-1}$, $v_\text{w}$ is $v_\text{e}$ scaled by $10,000 \text{ km s}^{-1}$, and $v_\text{w}^{-1}$ is $v_\text{w}$ scaled by $10 \text{ km s}^{-1}$.

Electrons and ions in plasma can reach CIE on the timescale of

$$n_\text{e} t \sim 10^{12} \text{ cm}^{-3} \text{ s},$$  \hspace{1cm} (4)

(e.g., Masai 1984; Smith & Hughes 2010). Note that only ions are presumed to be heated by the forward shock and electrons are heated up by the subsequent Coulomb interaction between ions and electrons. The timescale of the electron heating is (e.g., Masai 1994)

$$n_\text{e} t = 3 \times 10^{14} v_{\text{e},9}^3 \left( \frac{\mu}{0.5} \right)^{1.5} \left( \frac{\ln \Lambda}{30} \right)^{-1} \text{ cm}^3 \text{ s},$$  \hspace{1cm} (5)

where $\mu$ is the mean molecular weight and $\ln \Lambda$ is the Coulomb logarithm. Although the timescale of temperature equilibrium is a few orders of magnitudes longer than that of the CIE, the electron temperature can reach about 10% of the ion temperature ($\sim 10^9 \text{ K}$) in the CIE timescale (Masai 1994) and can become high enough to explain the ionization temperature of recombining SNRs. Recombining plasma in SNRs can appear if electrons cool down after CIE is achieved (e.g., Itoh & Masai 1989).

Figure 1 shows the comparison of the typical density in the shocked CSM (Equation (3)) and the CIE timescale (Equation (4)). CIE can be achieved at early epochs of SNRs from RSGs with typical mass-loss rate if we take into account the existence of the CSM. This is contrary to the general belief that it takes much time to achieve CIE because SNRs evolve in ISM. Note that $v_\text{e}$ in the early time is presumed to be higher than the value assumed in Figure 1 (e.g., Dwarkadas 2005) and this effect can make the evolution of the electron number density faster. In addition, the mass of the recombining plasma estimated from Figure 1 in the case of standard mass loss is $\lesssim 5 \times 10^{-2} M_{\odot}$ and rather small. Massive RSGs, yellow supergiants, or RSGs in binary systems can have higher mass-loss rates than less massive RSGs especially just before their explosions (see, e.g., Georgy 2012 and references therein) and they are more likely to become recombining SNRs among RSGs.

The early X-ray observations of Type IIb SN 1993J whose progenitor is an RSG in a binary system (e.g., Maund et al. 2004) revealed the existence of the CIE plasma a few days after the explosion (e.g., Uno et al. 2002) and the progenitor’s mass-loss rate is suggested to be $\lesssim 5 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ (e.g., Suzuki & Nomoto 1995; Fransson et al. 1996). This is consistent with our estimate, and explosions of RSGs can establish CIE in the early epochs and evolve to become recombining SNRs.

### 2.1.2. Wolf–Rayet Stars

The typical mass-loss rate and wind velocity of W-R stars are $\sim 10^{-5} M_{\odot} \text{ yr}^{-1}$ and $\sim 1000 \text{ km s}^{-1}$, respectively (e.g., Crowther 2007). If we assume that the wind from W-R stars is composed of 50% carbon and 50% oxygen and they are fully ionized when the CSM is shocked, $\rho_s = 3.3 \times 10^{-24} n_{\text{e}}$. With these values,
Figure 2. Evolution of the electron number density in the shocked CSM from W-R star winds. \(v_w = 10,000 \text{ km s}^{-1}\) and \(v_e = 1000 \text{ km s}^{-1}\) is fixed and lines with several mass-loss rates are shown. The distance in the horizontal axis is the distance which can be reached by the forward shock with \(v_s = 10,000 \text{ km s}^{-1}\). If we assume that the progenitor is in the W-R stage for 105 years before the explosion, the CSM can reach 100 pc with \(v_e = 1000 \text{ km s}^{-1}\). The dashed line follows \(n_{e,\text{ts}} = 10^{12} \text{ cm}^{-3} \text{s}^{-1}\) and corresponds to the minimum density required to reach CIE at the time. Shocked CSM above this line is presumed to be at CIE. (A color version of this figure is available in the online journal.)

The following equation is obtained from Equation (2):

\[
n_{e,\text{ts}}^2 = 6 \times 10^{17} M_{\odot} s v_{s,\text{ts}}^2 v_{w,\text{ts}}^{-1} \text{ cm}^{-3} \text{s}^{-2},
\]

where \(v_{w,\text{ts}}\) is \(v_w\) scaled by 1000 km s\(^{-1}\).

The evolution of \(n_{e,\text{ts}}\) is compared to the CIE timescale \(n_{e,\text{ts}} \sim 10^{12} \text{ cm}^{-3} \text{s}^{-1}\) in Figure 2. With the canonical mass-loss rate \(10^{-5} M_{\odot} \text{ yr}^{-1}\), the evolution of the shocked CSM can be comparable to the CIE timescale just after the explosion. However, \(v_s\) is presumed to be larger than \(v_s = 10,000 \text{ km s}^{-1}\) in the early epochs. If \(n_{e,\text{ts}}\) can be faster, it is likely that CIE is not achieved at early phases of the typical explosions of W-R stars with canonical mass-loss history. This is because the typical wind velocity is about 100 times larger than the typical RSG wind velocity and the CSM becomes thin much faster. Although recent radio observations of explosions of W-R stars (Type Ibc SNe) are revealing the existence of W-R stars with high mass-loss rates (\(~10^{-3} M_{\odot} \text{ yr}^{-1}\); e.g., Wellons et al. 2012), the amount of recombing plasma is very small (\(~10^{-3} M_{\odot}\); Figure 2) even if such a high mass-loss rate is maintained for the entire W-R phase. Thus, it may be difficult for W-R stars to have dense CSM massive enough to make them recombing SNRs. Since some elements can reach the CIE in smaller timescales than \(n_{e,\text{ts}} \sim 10^{12} \text{ cm}^{-3} \text{s}^{-1}\) at the typical temperature in shocked CSM (Smith & Hughes 2010), at least some elements may reach the CIE. In addition, it is also known that some W-R stars experience explosive mass loss just before their explosions which can eject massive CSM, as is indicated by the progenitor of Type Ibc SN 2006jc (e.g., Pastorello et al. 2007). Explosions of this kind of W-R star can also result in recombing SNRs but they are also expected to be rare.

2.2. Type IIn Supernova Progenitors

Type IIn SNe are SNe that show narrow spectral lines, especially of hydrogen, in optical spectra (e.g., Schlegel 1990). Their spectral features can be explained by the existence of the dense CSM with a Thomson optical depth \(\tau_T\) larger than 1 (e.g., Chugai 2001; Dessart et al. 2009). They can become luminous in X-ray and radio and some of them become luminous even in optical. The high luminosities of Type IIn SNe can be naturally explained by the interaction between SN ejecta and its dense CSM (e.g., Dwarkadas et al. 2010; Chugai et al. 2004) and the progenitors of Type IIn SNe are plausible candidates for originators of recombing SNRs.

We assume that Type IIn SNe have a dense CSM with \(\tau_T = \sigma_T \pi_{e,\text{ts}} \Delta R \sim 1\), where \(\sigma_T\) is the Thomson cross section, \(\pi_{e,\text{ts}}\) the mean CSM electron number density, and \(\Delta R\) is the CSM length. We use the mean density \(\pi_{e,\text{ts}}\) because the mass loss of Type IIn SN progenitors just before their explosions are revealed to be non-steady from X-ray observations (Dwarkadas & Gruszko 2012). The shock wave with velocity \(v_s\) can propagate through the CSM with \(t_s = \Delta R / v_s\). As CSM or ISM with much lower density exists outside the dense CSM and the shocked CSM is rarefied after the shock wave goes out of the dense CSM, recombing plasma can be easily synthesized once CIE is achieved in the shocked CSM. Assuming \(\pi_{e,\text{ts}} = 4\pi_{e,\text{ts}}\) and solar metallicity, the typical timescale before the rarefaction is

\[
\pi_{e,\text{ts}} t_s \sim 6 \times 10^{15} v_{s,\text{ts}}^{-1} \text{ cm}^{-3} \text{s}.
\]

This is much larger than the timescale required to achieve CIE, \(n_{e,\text{ts}} \sim 10^{12} \text{ cm}^{-3} \text{s}^{-1}\). In reality, \(v_s\) can be smaller than 10,000 km s\(^{-1}\) because of the deceleration by the dense CSM but this makes \(t_s\) longer. One caveat is that we used a constant mean electron density \(\pi_{e,\text{ts}}\) to estimate the density evolution. If the density declines very steeply, this assumption can be very crude and Type IIn SNe from very steep CSM may not end up with recombing SNRs. Nonetheless, many Type IIn SNe have flat density CSM (Dwarkadas & Gruszko 2012) and we presume that most Type IIn SNe can end up with recombing SNRs. However, as explosions of RSGs (Type II SNe) occurs much more frequently than Type IIn SNe (e.g., Li et al. 2011), the major progenitors of recombing SNRs are likely to be RSGs.

Unfortunately, the progenitors of Type IIn SNe are not well understood. Gal-Yam & Leonard (2009) have confirmed that the progenitor of a Type IIn SN, SN 2005gl, is a luminous blue variable (LBV; e.g., Humphreys & Davidson 1994). As LBVs originate from very massive stars (more than \(40 M_{\odot}\); where \(M_{\odot}\) is the zero-age main-sequence mass; e.g., Crowther 2007) and the observational rate of Type IIn SNe is consistent with the mass range of LBVs (e.g., Smith et al. 2011), Type IIn SNe are suggested to come mainly from these very massive stars. However, it is theoretically considered that LBVs are in an evolutionary stage in which very massive stars evolve to W-R stars and LBVs do not explode. It is also possible that the fast wind from a W-R star collides with the slowly moving wind from its previous RSG stage and a dense shell that is enough to be a Type IIn SN is created by the interaction (e.g., Dwarkadas et al. 2010). Another possible Type IIn SN progenitor is a super-asymptotic giant branch (AGB) star with \(M_{\odot} \sim 8 M_{\odot}\). An O+Ne+Mg core at the center of the super-AGB wind can be an electron-capture SN (Nomoto 1984). The progenitor of Type IIn SN 2008S is found to be around \(10 M_{\odot}\) (Prieto et al. 2008) and may belong to
this class (e.g., Botticella et al. 2009) but there also exists an argument that SN 2008S may not be an SN (Smith et al. 2009). Finally, we note that some of Type Ic superluminous SNe recently discovered (e.g., Quimby et al. 2011) are related to the interaction of a dense C+O-rich CSM and SN ejecta (Blinnikov & Sorokina 2010; Moriya & Maeda 2012) and they can also be a progenitor of recombining SNRs. However, Type Ic superluminous SNe preferentially appear in metal-poor galaxies (Quimby et al. 2011;Neill et al. 2011) and the occurrence rate is also quite small. Thus, recombining SNRs currently observed in our Galaxy seem irrelevant to them.

2.3. White Dwarfs

Although most of the recombining SNRs currently discovered are likely to originate from core-collapse SNe (e.g., Yamaguchi et al. 2012), Type Ia SNe can also evolve to become recombining SNRs although it is expected to be quite rare. Type Ia SNe are explosions of white dwarfs. There are two major suggested explosion paths for white dwarfs: single degenerate (SD) channel (e.g., Nomoto 1982) and double degenerate (DD) channel (e.g., Iben & Tutukov 1984). In the SD scenario, a white dwarf is in a binary system with a main-sequence star and the mass of the companion is accreted by the white dwarf. The white dwarf explodes when its mass gets close to the Chandrasekhar mass limit. On the other hand, the DD scenario suggests that Type Ia SNe are caused by the merger of two white dwarfs in a binary system. The main channel of Type Ia SNe is still unknown.

In the SD scenario, the exploding white dwarf is surrounded by the accreting materials with a typical rate of $\sim 10^{-7} M_\odot$ yr$^{-1}$ (Nomoto 1982) but the rate is presumed to be too small to make the recombining SNR. Mass loss from the companion star can also create CSM around the progenitor but the companion is likely to be a less evolved red giant with too-small mass-loss rates to establish CIE ($\sim 10^{-7} M_\odot$ yr$^{-1}$ or less; e.g., Hachisu et al. 1999). However, there are rare ways to make the mass-loss rate of the system high during the binary evolution (Hachisu et al. 2008) and some Type Ia SNe are actually suggested to be hybrids of Type Ia and Type IIn, i.e., Type Ia SNe that exploded in a CSM as dense as those discussed in Section 2.2 (e.g., SN 2002ic; Hamuy et al. 2003). Thus, it is possible that a Type Ia SN from the SD scenario evolves to a recombining SNR but the number is expected to be very small.

In the DD scenario, we do not expect the CSM from the progenitor system because two binary stars are white dwarfs. However, stripped materials at the time of the merger are suggested to remain when the merged white dwarf explodes (Fryer et al. 2010). These materials are quite dense ($n_{cw} > 10^{15}$ cm$^{-3}$ within $r = R_\odot$; see Figure 5 of Fryer et al. 2010) and Type Ia SNe exploding in such an environment can reach CIE and may end up with recombining SNRs. However, such a dense envelope is not obtained in a similar DD simulation of Pakmor et al. (2012). The fact that we do not see recombining SNRs of Type Ia SNe may already suggest that the model obtained by Fryer et al. (2010) is not the major path of becoming a Type Ia SN. Because of the uncertainty in the theoretical prediction of Type Ia SNe from the DD scenario, we still cannot exclude the possibility that Type Ia SNe from the DD scenario can be recombining SNRs.

To sum up, although all the recombining SNRs currently discovered are likely from core-collapse SNe, Type Ia SNe from both the SD and DD channels have the possibility of becoming recombining SNRs. When the detailed theoretical predictions are fixed, like the existence of the dense envelope in the DD channel, recombining SNRs may be able to be a probe to indicate the progenitor system of Type Ia SNe.

3. CONCLUSIONS

We have investigated the possible progenitors of recombining SNRs. If a CSM which is dense enough to establish CIE in the early epochs of the SNR evolution exists around a progenitor, the plasma in the shocked CSM can be overionized and the SNR can become a recombining SNR. RSGs, especially massive ones, and Type IIn SN progenitors can have the CSM dense enough to establish CIE at the early stage of their explosions and can evolve to become recombining SNRs. As explosions of RSGs (Type II SNe) occurs much more frequently than Type IIn SNe, the major progenitors of recombining SNRs are likely to be RSGs.

It is difficult for W-R stars and white dwarfs to produce recombining SNRs with their standard mass-loss histories but it is suggested that they have mechanisms to enhance their mass-loss rates and they can become recombining SNRs if such mechanisms enhance their mass-loss rates. However, these mechanisms are presumed to work only on a small fraction of these stars and thus such progenitors are expected to be a minor way of creating recombining SNRs.

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