Evolution of Supernova Remnants Expanding out of the Dense Circumstellar Matter into the Rarefied Interstellar Medium

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Abstract

We carried out 3D-hydrodynamical calculations for the interaction of expanding supernova ejecta with the dense circumstellar matter (CSM) and the rarefied interstellar medium (ISM) outside. The CSM is composed of stellar-wind matter from the progenitor in its pre-supernova phase, and assumed to be axially symmetric: more matter around the equator than in the polar direction driven by rotation of the progenitor. Because of the high density of the CSM, the ionization state of the shock-heated ejecta quickly becomes equilibrium with the electron temperature. When the blast wave breaks out of the CSM into the rarefied ISM, the shocked ejecta cools rapidly due to adiabatic expansion, and hence an over-ionized/recombining plasma would be left. The ejecta is reheated by the second reverse shock due to the interaction with the ISM. We calculated the emission measure of the supernova remnant (SNR) along the line of sight, and found that the over-ionized plasma appears to be bar-like with wings in the edge-on (equatorial view), while shell-like in the face-on (polar view) geometry with respect to the rotation axis. Hot gas heated by the blast wave exists in the outermost region of the SNR with a nearly complete shell, but the X-rays therefrom are too faint to be observable. Thus, depending on the viewing angle, the SNR of the over-ionized plasma would exhibit a center-filled morphology in X-rays, like W 49 B, a mixed-morphology SNR. The bar-like structure is swept out by the second reverse shock and disappears eventually, and then the SNR becomes shell-like in both the equatorial and polar views in the later phase of evolution.

Key words: hydrodynamics — ISM: supernova remnants — methods: numerical — stars: circumstellar matter

1. Introduction

The evolution of a supernova remnant (SNR) with no neutron star in its center is described essentially by shock waves propagating outward (blast wave) into the ambient matter and inward (reverse-shock wave) into the supernova ejecta. In young SNRs, the shocked matter is heated up to temperatures higher than $10^7$ K, and forms an optically-thin hot plasma. This plasma emits X-rays with many emission lines of highly ionized heavy elements. Since the time-scale of ionization by electron impact is longer than that of shock-heating of electrons, the X-ray spectra of young SNRs exhibit ionization states lower than those expected from the electron temperatures, which is called under-ionized or ionizing. The ionization state is represented by the ionization temperature, $T_\mathrm{z}$, the plasma temperature in collisional ionization equilibrium having the relevant ionization state. Thus, many young SNRs show $T_\mathrm{z} < T_\mathrm{e}$ (under-ionized/ionizing) for the electron temperature, $T_\mathrm{e}$.

Contrary to the above-mentioned standard scenario, Kawasaki et al. (2002) found an over-ionized plasma ($T_\mathrm{z} > T_\mathrm{e}$) in the ASCA observation from a mixed-morphology SNR, IC 443. They proposed that thermal conduction from the hot interior of the remnant to the cold exterior can explain the over-ionized plasma. Kawasaki et al. (2005) further investigated five other mixed-morphology SNRs (W 49 B, W 28, W 44, 3C 391, and Kes 27), and found that W 49 B shows $T_\mathrm{z} > T_\mathrm{e}$ as well.

Suzaku detected clear spectral structures of radiative-recombination continua, direct evidence for recombining plasmas, in the X-ray spectra of IC 443 (Yamaguchi et al. 2009) and W 49 B (Ozawa et al. 2009). Radiative recombination continua, and hence an over-ionized plasma, was also found in another mixed-morphology SNR, G359.1–0.5 (Ohnishi et al. 2011). Although the samples are still limited, the over-ionized plasmas are all found in the mixed-morphology SNRs associated in or near the star-forming complex with H II regions and molecular clouds. Hence, these SNRs are likely to be due to core-collapse supernovae; the over-ionized plasma is possibly related to the massive progenitor and/or its environments.

One possibility is that the ionization by photons of a few tens keV at the initial phase of the explosion of massive stars, e.g., possible X-ray flash or afterglow of $\gamma$-ray bursts, is responsible for the over-ionized state. Another possibility is rarefaction in the adiabatic evolution phase of the SNR; when the shock wave breaks out of the dense circumstellar matter (CSM), like the progenitor’s stellar wind, into the rarefied interstellar medium (ISM), the shock-heated electrons would rapidly cool due to adiabatic expansion, leaving highly ionized states (Itoh & Masai 1989).

In the present work, we investigate the latter possibility. Itoh and Masai (1989) calculated the SNR evolution and radiation...
for a spherically symmetric structure. We extend this work to non-symmetric structures, as are found in mixed-morphology SNRs. Unlike Itoh and Masai (1989), we do not take ionization or radiation processes into account; we assume the relevant SNR evolution is fully adiabatic. We describe the model in the following section. The calculations and results are presented in section 3, and discussed in section 4. We give a summary in section 5 and notes about electron temperature in the Appendix.

2. Model

2.1. Circumstellar Matter

In a core-collapse supernova, the massive progenitor (red or blue supergiant or Wolf-Rayet star) is expected to blow a strong stellar wind in its pre-supernova phase, and to form dense CSM around the progenitor. If the stellar wind is spherically symmetric with a mass-loss rate, $\dot{M}$, and wind velocity, $v_w$, the CSM density, $\rho$, at a distance $r$ from the progenitor is given by

$$\rho = \frac{\dot{M}}{4\pi v_w r^2}. \quad (1)$$

For a while before the supernova explosion, the stellar wind ceases. Then, the stellar wind forms a thick shell. The inner and outer radii of the shell are given by $R_{in} = v_w t_w$ and $R_{out} = v_w (t_w + t_e)$, respectively (see figure 1), where time $t_w$ and $t_e$ are the duration of the wind activity and the elapsed time after the wind ceases, respectively.

In realistic stellar winds, more matter around the equatorial plane than in the polar direction at the same distance. For the progenitor of SN 1987A, Blondin and Lundqvist (1993) suggested that the ratio of the equatorial to polar mass-loss rate was at least 20 during its red supergiant stage. This value corresponds to $a \approx 4.5$. In our calculations we adopted values of from 1 to 3.

We calculated the evolution for the following five models:

A1 Isotropic CSM same as Itoh and Masai (1989) for a reference.

A2 Anisotropic CSM concentrated around the equatorial plane.

A3 Same as A2, but more mass around the equatorial plane.

B1 Same as A2, but with a lower density ISM.

B2 Same as B1, but with a higher wind velocity.

The numerical values for each model are given in table 1, where the values of $R_{in}$, $R_{out}$, $\rho_{in}$, and $\rho_{out}$ are those on the equatorial plane. The mass-loss rate is assumed to be $5 \times 10^{-5} M_{\odot} \text{yr}^{-1}$, the same as that of Itoh and Masai (1989), for all the models.

2.2. Supernova Ejecta

We focus on the effect of the CSM, particularly for an anisotropic CSM, on the early phase evolution of SNRs. For the supernova ejecta, we simply assume a spherical distribution with a core of radius of $R_{ej}$ and an extended envelope of radius $R_{ej}$, as (Truelove & McKee 1999)

$$\rho = \frac{3 M_{ej}}{4 \pi v_{ej}^2 t^3} \frac{1 - n/3}{1 - (n/3) w_{ej}^2 - n}$$

$$\times \left\{ \begin{array}{ll}
  \frac{w_{ej}^{-n}}{[r/(v_{ej} t)]^{-n}} & \text{for } r < R_{ej} \\
  \frac{1}{w_{ej}} & \text{for } R_{ej} \leq r \leq R_{ej},
\end{array} \right. \quad (3)$$

where

$$v_{ej} = \left( \frac{2 E_{ej}}{M_{ej}} \right)^{1/2} \left( \frac{5 - n}{3 - n} \right)^{1/2} \left( \frac{w_{ej}^{-(3-n)} - n/3}{w_{ej}^{-(5-n)} - n/5} \right)^{1/2} \frac{1}{w_{ej}} \left( \frac{2}{\gamma} \right)$$

is the expansion velocity at $R_{ej}$. $M_{ej}$ and $E_{ej}$ are the ejecta mass and the explosion energy (kinetic energy), respectively. These are assumed to be $E_{ej} = 2 \times 10^{51} \text{erg}$ and $M_{ej} = 10 M_{\odot}$. The other parameters, $n$ and $w_{ej} = R_{ej}/v_{ej}$, are taken to be 6 and 0.49, respectively. All of these values are the same as those of Itoh and Masai (1989), and hence $v_{ej} \approx 8.5 \times 10^8 \text{cm s}^{-1}$.

3. Calculation and Results

We numerically solved the Euler equations utilizing the athena3d code (Stone et al. 2008):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\frac{1}{\rho} \nabla p,$$

$$\frac{\partial}{\partial t} \left[ \rho \left( \frac{1}{2} v^2 + u \right) \right] + \nabla \cdot \left[ \rho \mathbf{v} \left( \frac{1}{2} v^2 + u + \frac{p}{\rho} \right) \right] = 0,$$

where $\rho$, $p$, $\mathbf{v}$, and $u$ are the mass density, the pressure, the fluid velocity, and the internal energy per unit mass, respectively.

The equation of state is written as $p = (\gamma - 1)\rho u$ with $\gamma = 5/3$,
The blast shock and reverse shock heat the CSM to a fairly good agreement with that of Itoh and Masai (1989). Simply assuming adiabatic evolution, the evolution of model A1 differs from that of model B1, as shown in figure 2. The mean temperature of the shocked ISM drops at 23 yr and 270 yr, but turns to rise by the second reverse shock at 770 yr, but turns to rise by the second reverse shock at 280 yr and 770 yr, but turns to rise by the second reverse shock at 920 yr in the polar and equatorial directions, respectively. Similarly to the other models, the temperature of the shocked ejecta drops at 23 yr and 68 yr by the break-out, but turns to rise at 810 yr and 1800 yr in the polar and equatorial directions, respectively.

3.1. Model A1

Although we included neither ionization nor radiation and simply assumed adiabatic evolution, the evolution of model A1 is in fairly good agreement with that of Itoh and Masai (1989). The blast shock and reverse shock heat the CSM to $T \gtrsim 10^8$ K, and the ejecta to $T \gtrsim 10^7$ K, respectively. The blast wave expands as $r_b \propto t^{0.88}$, while $v_\infty \propto t^{0.87}$ in Itoh and Masai (1989), where $r_b$ is the blast-wave radius.

The blast wave breaks out at 41 yr, 2 yr earlier than in Itoh and Masai (1989), who took radiation loss into their calculation. After the break-out, the blast wave rapidly expands adiabatically, and hence the temperature and density of the shocked matter decrease approximately as $T \propto t^{-2}$ and $\rho \propto t^{-3}$ for $\gamma = 5/3$.

When the pressure of the shocked CSM becomes below that of the shocked ISM, a second reverse shock occurs to propagate inward, and reheats the CSM and ejecta. The second reverse shock reaches the ejecta at 830 yr, 120 yr earlier than in Itoh and Masai (1989).

3.2. Models A2 and A3

The evolution is basically the same as model A1, but is dependent on direction: more matter on the equatorial plane than in the polar direction. With increasing the value of $a$, the break-out occurs earlier in the polar and later in the equatorial direction than in model A1. The former is due to a shorter distance to the CSM, and the latter is a higher density of the CSM than those in model A1. In addition, the second reverse shock reaches the ejecta earlier in the polar direction and later in the equatorial direction than in model A1. In model A2, the break-out occurs at 17 yr in the polar direction, and at 46 yr in the equatorial direction, as shown in figure 2. The mean temperature, $T_b$ of the shocked ejecta turns to rise at 340 yr and 1100 yr, in the polar and equatorial directions, respectively.

3.3. Model B1

The break-out occurs at the same time as in model A2, since the CSM distribution is the same as in model A2. The difference of model B1 from model A2 is the lower density of the ISM by an order of magnitude. The velocity of the blast wave after the break-out is slightly higher than that in model A2, and the second reverse shock occurs later. The temperature $T$ of the shocked ISM is about one-fifth of that in model A2, and the second reverse shock occurs later. The temperature $T$ of the shocked ejecta drops at 23 yr and 68 yr by the break-out, but turns to rise at 810 yr and 1800 yr in the polar and equatorial directions, respectively.

3.4. Model B2

The difference from model B1 is the lower density of the CSM by three orders of magnitude due to a higher wind velocity by an order of magnitude. Even at such low densities, the break-out occurs at 170 yr and 450 yr in the polar and equatorial directions, respectively. Similarly to the other models, the temperature $T$ of the shocked ejecta drops at 280 yr and 770 yr, but turns to rise by the second reverse shock at 920 yr and 2400 yr in the polar and equatorial directions, respectively.

### Table 1. Parameters of circumstellar matter and interstellar medium.*

| Model | CSM | ISM |
|-------|-----|-----|
|       | $a$ | $R_{in}$ (10$^{16}$ cm) | $R_{out}$ (10$^{16}$ cm) | $\rho_{in}$ (amu cm$^{-3}$) | $\rho_{out}$ (amu cm$^{-3}$) | $v_w$ (cm s$^{-1}$) | $\rho_{ISM}$ (amu cm$^{-3}$) |
| A1    | 1   | 2.0 | 92.6 | $3.4 \times 10^2$ | $1.6 \times 10^2$ | $10^6$ | $1.6 \times 10^{-1}$ |
| A2    | 2   | 2.0 | 92.6 | $6.9 \times 10^5$ | $3.2 \times 10^5$ | $10^6$ | $1.6 \times 10^{-1}$ |
| A3    | 3   | 2.0 | 92.6 | $1.0 \times 10^6$ | $4.8 \times 10^2$ | $10^6$ | $1.6 \times 10^{-1}$ |
| B1    | 2   | 2.0 | 92.6 | $6.9 \times 10^5$ | $3.2 \times 10^5$ | $10^6$ | $1.6 \times 10^{-2}$ |
| B2    | 2   | 20  | 926  | $6.9 \times 10^2$ | $3.2 \times 10^{-1}$ | $10^7$ | $1.6 \times 10^{-2}$ |

* Mass loss rate $\dot{M}$ is $5 \times 10^{-5} M_{\odot}$ yr$^{-1}$ in all the models, and $\rho_{in} = \rho(\tau = R_{in}), \rho_{out} = \rho(\tau = R_{out})$. 

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4. Discussion

In table 2 we summarize the temperatures and blast-wave radii at characteristic epochs, \( t_b \) and \( t_d \) (see below), for each model.

4.1. Dynamical Evolution

Before the break-out, the evolution of an SNR can be described by a self-similar solution, and the blast wave expands as \( r_b \propto t^\alpha \). Almost independently of the anisotropy of the CSM (models A1–A3), the values of \( \alpha \) are close to each other in both the polar and equatorial directions, as can be seen in the upper panel of figure 3. After the break-out, the \( \alpha \) values are slightly larger in larger \( \alpha \) models, but approach the value of model A1 (\( \alpha = 1 \)) with time. This implies that the blast wave approaches spherical symmetry with time, and the ratio of the blast-wave radius of the polar to equatorial direction becomes less than \( \sim 1.2 \) in 1000 yr in any model of ours here.

If the density difference across the interface between the CSM and ISM is large enough (models A1–A3 and B1), the blast wave becomes faster just after the break-out by a factor of \( \sim 2 \), almost independent of the density difference. On the other hand, if the density difference is as small as model B2, the velocity increases by a factor of \( \sim 1.4 \). The expansion velocity of a spherical fluid initially at rest asymptotically approaches its maximum value of \( 2c_s/\gamma - 1 \), where \( c_s \) is a sound speed of the fluid (Zel’dovich & Raizer 1966). Similarly, denoting the shock velocity by \( V_S \), we may have the maximum expansion velocity after the break-out, as

\[
\frac{2}{\gamma - 1} \left[ c_s^2 + V_S^2(t_b) \right]^{1/2} \simeq 2.0 V_S(t_b),
\]

where \( V_S(t_b) \) is the shock velocity of the blast wave immediately after the break-out at \( t = t_b \). Here, we take the Rankine–Hugoniot relation of strong shocks into account. This estimate is consistent with the result of our hydrodynamical calculation. The high shock velocity and rarefaction caused by the break-out may be in favor of particle acceleration, because the former boosts the maximum energy of particles, and the latter works for particles to become non-thermal.

4.2. Temperature and Ionization State

As demonstrated by Itoh and Masai (1989), rarefaction by the blast-wave break-out rapidly cools the shock-heated matter to be an over-ionized/recombining plasma of \( T_e < T_z \). This recombining plasma state lasts until the second reverse shock reheats the matter to \( \geq T_z \). Although ionization is not calculated simultaneously with hydrodynamics, we can analyze the ionization state, i.e., ionizing, equilibrium, or recombining, of the shocked matter from the electron temperature and density. The ionization state thus evaluated is consistent with Itoh and Masai (1989), considering the variation of the epochs and duration, which depend on the CSM/ISM models, as discussed in the previous sections.

The upper panels of figures 4a (model B1) and 4b (model B2) show the evolution of the ion and electron temperatures averaged over the shocked matter of the ejecta. Before the break-out, \( T_e \) becomes nearly equal to \( T_i \) due to the high densities of the CSM. Also, after the break-out and until
arrival of the second reverse shock, $T_{\text{e}}$ is nearly equal to $T_{i}$, because cooling is due to adiabatic expansion. By the second reverse shock, $T_{i}$ rises faster than $T_{\text{e}}$, and then $T_{e}$ rises through the energy transport from ions, as shown in the upper panels of figure 4.

In the lower panels, we show the average density of the shocked ejecta by the solid line. Ionization by electron-impact becomes equilibrium with the time-scale $\tau$ given by $\rho \tau \sim 10^{12}\text{amu cm}^{-3}\text{s}$, almost independent of the temperature or ion species (Masai 1994). We also plot this relation as $\rho_{\text{crit}} = 10^{12}t^{-1}\text{amu cm}^{-3}$ with the dashed line in the lower panels. Well before the break-out, since the density is high enough ($\rho > \rho_{\text{crit}}$) due to the presence of CSM, ionization quickly reaches its equilibrium at $T_{\text{e}}$, i.e., $T_{z} \sim T_{\text{e}}$.

As the SNR expands, the average density of the shocked matter decreases approximately as $\rho \propto t^{-2}$. When rarefication occurs by the break-out, $\rho$ decreases faster as $\propto t^{-3}$ (see subsection 3.1). Therefore, $\rho$ becomes below $\rho_{\text{crit}} \propto t^{-1}$, as can be seen in the lower panels of figure 4, and $T_{z}$ is decoupled from $T_{e}$. In other words, recombination no longer follows the rapid decrease of the electron temperature, and the ionization state freezes roughly at $T_{z} \sim T_{e}(t_{4})$, where $t_{4}$ is the epoch at which $\rho = \rho_{\text{crit}}$.

The decoupling epoch, $t_{4}$, is also shown in the lower panels of figure 4 with the thin-dotted vertical line. In model B1, $t_{4} \sim 190\text{yr}$ in the equatorial direction. Note that $t_{4} > t_{b}$ and $T_{e}(t_{4}) < T_{e}(t_{b})$ in model B1, where $T_{e}(t_{b})$ is the electron temperature immediately before the break-out. Models A1–A3 show the similar behavior to model B1 described here.

In model B2, unlike other models or Itoh and Masai (1989), the CSM is located away from the progenitor, and hence the density is low. Therefore, the break-out occurs later, but $\rho$ becomes below $\rho_{\text{crit}}$ earlier than in model B1. As can be seen in figure 4b, $t_{4} < t_{b}$ in model B2, and $t_{4} \sim 70\text{yr}$ in the equatorial direction. In fact, as is seen in the upper panel, $T_{e}$ before the break-out is nearly constant at $\sim T_{e}(t_{b})$ in model B2. As a result, the ionization temperature of the recombining plasma is higher in model B2 than that in model B1.

When the second reverse shock reaches the ejecta, the temperature turns to rise, as can be seen in the upper panels of figure 4. If the electron temperature exceeds, or becomes comparable to, $T_{e} \sim T_{e}(t_{4})$, the ionization state turns to be ionizing or nearly equilibrium. This is the case for models A1–A3 with a higher ISM density. In model B1, though the ISM density is low, $T_{e}$ exceeds $T_{e} \sim 3000\text{yr}$ owing to the dense CSM and lower $T_{z}$. On the other hand, in model B2 the density is too low for the second reverse shock to raise $T_{e}$ in such short time, and the over-ionization state remains much longer. If $T_{e}$ becomes higher than $2T_{z}$ at the shock front, $T_{z}$ may be attained by the energy transfer from ions. Since $T_{i} \propto V_{S}^{2}$ (reverse shock) decreases with the age, however, the recombining state would last yet for thousands of years.

After becoming decoupled from the electron temperature, the ionization temperature decreases by recombination with time-scale $\tau$. We note here that the recombination time-scale of $\sim 10^{4}\text{yr}$ (Masai 1994) is longer than the age of over-ionized SNRs: $\sim 4000\text{yr}$ for IC 443 (Troja et al. 2008) and 1000–4000 yr for W 49 B (Pye et al. 1984; Smith et al. 1985; Hwang et al. 2000).

4.3. X-Ray Emission Measure Distribution

All SNRs with over-ionized/recombining plasma so far observed are mixed-morphology SNRs, which exhibit center-filled X-ray emission and shell-like radio emission. Hence, we investigated the distribution of the X-ray emission measure for SNRs with anisotropic stellar wind. We integrated the density square along the line of sight, as $\int \rho^{2}dl$. We show a map (black lines) for model B2 in figure 5. Here, the shocked matter of $T > 10^{6}\text{K}$, which is responsible for X-ray emission, was taken into the calculations.

At ages 980 yr and 1800 yr, we can see a bar-like structure (horizontal) with diffuse wings in the equatorial view, while a thin shell appears in the polar view. The emission measure is dominated by shock-heated ejecta, which is a recombining plasma, as can be seen from figure 4b. The temperature dependence of the line emissivity is weaker in recombining than in

![Fig. 4. Model (a) B1 and (b) B2: Averaged temperature and density of the shocked ejecta in the equator (left) and polar (right) directions, as functions of the elapsed time after explosion. Upper: The solid and broken lines represent the electron and ion temperatures, respectively. Lower: The solid and dashed lines represent the density and $\rho_{\text{crit}} = 10^{12}t^{-1}\text{amu cm}^{-3}$, respectively, and the thin-dotted vertical lines represent the decoupling epoch, $t_{4}$ (see text).](https://academic.oup.com/pasj/article-abstract/64/2/24/1480245)

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equilibrium, and the emission-measure map reflects roughly the X-ray surface brightness.

The bar structure is clearer at younger ages after the break-out, and diffuses out gradually with time. At 1800 yr, the second reverse-shock front appears to surround the bar/wing structure out. Hence, the late-phase structure, and thereby the bar-end structure becomes distorted. The second reverse-shock propagates inward, and eventually sweeps the bar/wing structure out. Hence, the late-phase SNR approaches shell-like both in the equatorial and polar views, as can be seen at 10000 yr in figure 5, where a little elongated shape with a narrow middle part is still seen in the equatorial view.

W 49 B shows a bar-like structure as well as a recombinating plasma state (Ozawa et al. 2009). The bar and its east-end observed with Chandra (Keohane et al. 2007) look similar to our calculation shown in figure 5. We thus suggest that W 49 B is the case of a nearly equatorial view for the supernova remnant of a massive progenitor that exploded in its past stellar wind. It should be noted that, in our calculation, the structure of the bar-end is formed by the reverse shock, not by collisions with a molecular cloud near the bar-end.

The grey lines in figure 5 represent the low-level emission measure drawn linearly from zero, every $10^{16}$ amu cm$^{-2}$ to the maximum $1.0 \times 10^{27}$ amu cm$^{-2}$ at 980 yr, every $1 \times 10^{16}$ amu cm$^{-2}$ up to $1.0 \times 10^{27}$ amu cm$^{-2}$ at 1800 yr, and every $1 \times 10^{16}$ amu cm$^{-2}$ up to $1.0 \times 10^{27}$ amu cm$^{-2}$ at 1800 yr. The horizontal and vertical axes show the scale in units of pc.

5. Conclusion

We investigated the evolution of SNRs that explode in the progenitors’ stellar wind matter, while considering possible environments of mixed-morphology SNRs with over-ionized plasmas. We here summarize the results:

Fig. 6. Electron temperature vs. radius of SNRs that have no active central sources. Open and filled circles represent shell-like and mixed-morphology SNRs, respectively; line-connected two circles mean the data by two-temperature analysis. The thin and thick solid/broken lines represent the calculations for the density $\rho = 0.1$ amu cm$^{-3}$ and $\rho = 1$ amu cm$^{-3}$, respectively, of the ambient matter. References — Kepler: Kinugasa and Tsunemi 1999, G15.9+0.2: Reynolds et al. 2006, G27.4+0.0: Gotthelf and Vasisht 1997, Cygnus Loop: Miyata et al. 2007, G109.1+1.0: Sasaka et al. 2004, Cassiopeia A: Kawasaki et al. 2005, Tycho: Hwang and Gotthelf 1997, G156.2+5.7: Katsuda et al. 2009, Puppis A: Tamura 1995, G272.2–3.2: Harrus et al. 2001, G299.2–2.9: Park et al. 2007, RCW 86: Rho et al. 2002, SN 1006: Yamaguchi et al. 2008, Lupus Loop: Park et al. 2009, CTB 37 A: Aharonian et al. 2008, CTB 37 B: Nakamura et al. 2009, G349.7+0.2: Lazendic et al. 2005, W 28: Kawasaki et al. 2005, W 44: Kawasaki et al. 2005, 3C 400.2: Saken et al. 1995, Kes 27: Enoguchi et al. 2002, MSH 11—61 A: Rho and Petre 1998, 3C 391: Kawasaki et al. 2005, CTB 1: Rho and Petre 1998, W 51 C: Koo, Kim, and Seward 1995, CTA 1: Rho and Petre 1998, W 63: Rho and Petre 1998, HB 21: Rho and Petre 1998, IC 443: Yamaguchi et al. 2009, Kes 79: Rho and Petre 1998, HB 3: Rho and Petre 1998, G327.1+1.1: Sun, Wang, and Chen 1999, W 49 B: Ozawa et al. 2009, 3C 397: Rho and Petre 1998, MSH 11—54: Rho and Petre 1998.
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- When the blast wave breaks out of the wind matter into the ambient ISM, the shocked matter cools rapidly due to adiabatic expansion. Just after the break-out, the expanding velocity becomes faster by a factor of up to two, and then gradually decreases to that of the extrapolated from the velocity trend before the break-out.
- Before the break-out, the shocked matter reaches ionization equilibrium and equipartition, $T_e \sim T_i$, but deviates from the equilibrium by rarefaction after the break-out. Consequently, the shock-heated ejecta turns to be a recombining plasma, since cooling due to adiabatic expansion is much faster than recombination.
- The recombining state of the shocked ejecta lasts until the second reverse shock, which occurs by the interaction with the ISM, propagates inward and reheats the ejecta. If the density of the ejecta is too low to establish ionization equilibrium, however, the recombining state lasts longer.
- After the break-out in the adiabatic phase, since the emission measure of the shocked ejecta is much larger than that of the shocked ambient matter, the SNR in X-ray wavelengths appears to be much brighter in the reverse-shocked inner region than the blast-shocked outer shell.
- When the stellar wind matter is not isotropic, but denser in the equatorial direction due to the progenitor’s rotation, the SNR in the recombining state appears to be bar-like with wings in the equatorial view, and thin shell-like in the polar view. Thus the SNR would show various center-filled shapes in X-rays, depending on the viewing angle. On the other hand, the blast-shocked matter, which is very faint in X-rays, but could be observed in radio, forms a fairly complete shell outside.
- As the SNR age increases, however, the second reverse shock sweeps the bar/wing structure out and merges into the whole ejecta eventually. Hence, the bar/wing structure disappears and the late-phase SNR would appear to be shell-like almost independently of the viewing angle.

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Appendix. Electron Temperatures of SNRs

In the present work, we assume that shocks substantially heat ions at the shock front, and then the electron temperature rises through energy transport by Coulomb collisions and diffusion in the post-shock region. In figure 6 we compare the electron temperature thus obtained (Masai 1994) by the solid lines and temperature in the equipartition with ions at the shock front by the broken lines, with the observed electron temperatures (the circles). One can see that the transfer by Coulomb collisions from ions to electrons is a reasonable assumption to account for the observed data.

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