Part 2

Supernova Remnants

Young Neutron Stars and Their Environments
IAU Symposium, Vol. 218, 2004
F. Camilo and B. M. Gaensler, eds.

Supernova Remnants: An Introductory Review

Jacco Vink[1,2]

[1] *Columbia Astrophysics Laboratory, Columbia University, 505 West 120th Street, New York, NY 10027, USA*

[2] *Chandra Fellow; Present address: SRON, Sorbonnelaan 2, 3584CA Utrecht, Netherlands*

Abstract. The two main aspects of supernova remnant research addressed in this review are: I. What is our understanding of the progenitors of the observed remnants, and what have we learned from these remnants about supernova nucleosynthesis? II. Supernova remnants are probably the major source of cosmic rays. What are the recent advances in the observational aspects of cosmic ray acceleration in supernova remnants?

1. Introduction

The study of supernova remnants (SNRs) has many facets that are of a broad astrophysical interest. As supernova ejecta can be directly observed in young and medium-aged SNRs, they are an important tool for testing supernova nucleosynthesis and explosion models. This is not only important for a better understanding of the chemical evolution of the universe, but also for studying the evolution of spacetime itself, as Type Ia supernovae (SNe) are used as standard candles. Furthermore, SNe provide kinetic energy to the interstellar medium, an important ingredient for star formation.

SNR shocks are also of interest as they are likely to be the principle sites of cosmic ray (CR) acceleration, at least up to "the knee" in the CR spectrum ($\sim 3 \times 10^{15}$ eV). This requires that about 10% of the initial kinetic energy of a SN, typically 10^{51} ergs, is used to accelerate particles. Whether SNRs are the source of CRs is still open to debate, as especially the "knee" energy is hard to reconcile with X-ray and TeV gamma-ray observations.

Finally, it is worth pointing out that core-collapse SNe mark the birth of a stellar remnant. Studying remnants with pulsars is therefore of considerable interest, as one can better constrain the age of the pulsar (often in disagreement with the characteristic pulsar age $\tau = P/2\dot{P}$, e.g., Pavlov et al. 2002), which may give new insights into the distribution of initial periods, and in the possible connections between pulsar and progenitor properties. The fact that magnetars candidates are often found in SNRs emphasizes the connection between SNR and pulsar research.

In this review I concentrate on the shell-type SNRs, as there are many contributions in these proceedings dealing with neutron stars and their interaction with SNRs. I limit this review to a few well studied SNRs, as past and recent

https://doi.org/10.1017/S0074180900180581 Published online by Cambridge University Press

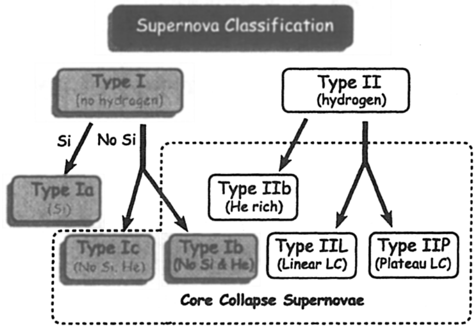

Figure 1. The supernova classification scheme.

advances in this field have mostly come from the brightest SNRs, which can be studied in sufficient detail.[1]

2. Supernova Remnants and Their Progenitors

Figure 1 shows the current SN classification scheme, which is largely based on optical spectroscopy. However, a more meaningful classification is based on the underlying explosion mechanism. One can then define two broad classes. On the one hand there are the core-collapse SNe, i.e. caused by the implosion of a massive star's core. In this case the energy for the explosion is provided by the release of gravitational energy, most of which ($> 10^{53}$ ergs) is released in the form of neutrinos. Core-collapse SNe are expected to create neutron stars or a black holes. All of the SNe in Figure 1, except Type Ia, are core-collapse SNe. The reason that Type Ib/c SNe do not have hydrogen in their spectra is attributed to stellar mass loss of the progenitor, which has removed the H-rich envelope. Type Ia SNe, on the other hand, are likely to be caused by the thermonuclear disruption of a C-O white dwarf, but neither the nature of the binary system, nor the disruption mechanism (detonation, deflagration, delayed detonation) is yet known (Branch et al. 1995). However, in order to disrupt a white dwarf, at least 0.35 $M_\odot$ of C-O needs to be burned into ^{56}Ni, which should be observable in SNRs as its daughter product, ^{56}Fe.

Identifying a remnant with a SN type is often difficult. The reason is that, although thermonuclear and core-collapse SNe have different explosion mechanisms, their kinetic energy output is similar. However, if a neutron star is associated with the SNR it is clear that it is a core-collapse remnant. In all other cases one has to rely on abundance measurements in comparison with explosion models (e.g., Woosley & Weaver 1995; Nomoto et al. 1997), or on external factors, such as the proximity of an OB association. However, for a number of remnants reasonable inferences can be made about the SN type. In particular, X-ray spectroscopy is very useful for abundance studies, as most of

[1]Dr. D. Green maintains a list of all Galactic SNRs at
`http://www.mrao.cam.ac.uk/surveys/snrs` (see also Stephenson & Green 2002).

https://doi.org/10.1017/S0074180900180581 Published online by Cambridge University Press

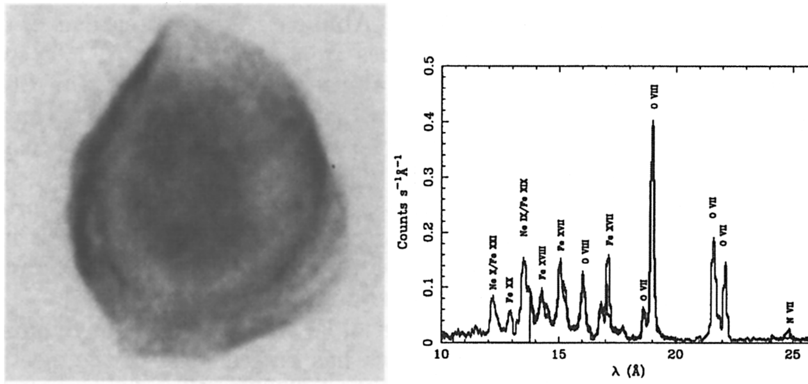

Figure 2. *Chandra* image of DEM L 71 in Fe-L emission (left; see Hughes et al. 2003 for a color version), and a high-resolution *XMM-Newton* RGS spectrum (after van der Heyden et al. 2003).

the shocked mass emits X-rays, and important α-elements between O and Fe have prominent lines in the soft X-ray band.

2.1. Type Ia Remnants

One of the characteristics to be expected for Type Ia remnants is the presence of $\sim$ 0.5 $M_\odot$ of Fe. In most SNRs, Fe emits lines in the range 0.8–1.2 keV (Fe-L, Fig. 2) and Fe-K emission from 6.4–7 keV. The Fe-L emission consists of many lines giving rise to a bump in X-ray spectra observed with CCD detectors such as on *ASCA*, *XMM-Newton*, and *Chandra*. Hughes et al. (1995) noted that LMC remnants fall into two classes, those with prominent Fe-L emission and those without. The Fe-L dominated remnants are likely Type Ia remnants. However, one should be careful in applying this method. For example, Kepler's remnant would be accepted as a Type Ia remnant, whereas optical spectroscopy of Kepler shows the presence of N overabundance suggesting a core-collapse remnant (Bandiera & van den Bergh 1991). Another example is Tycho's SNR (SN 1572), which is generally accepted to be a Type Ia remnant, but which lacks prominent Fe-L emission. However, Tycho's X-ray spectrum does show Fe-K emission, which peaks at a smaller radius than the spectral lines of other elements. This clearly indicates that there is an elemental stratification, just as expected for Type Ia remnants, with an inner ejecta layer consisting of Fe and the outer ejecta of mid-Z elements (Hwang & Gotthelf 1997). The lack of Fe-L emission from Tycho can be attributed to the low ionization age of the plasma.[2]

A similar lack of Fe-L emission from another historical Type Ia remnant, SN 1006, can also be attributed to the low ionization age of $n_e t \sim 2 \times 10^9$ cm^{-3} s (Vink et al. 1999; Dyer et al. 2001; Long et al. 2003). Both Dyer et al. (2001) and Long et al. (2003) did report an overabundance of Fe, but high resolution spectroscopy with the *XMM-Newton* RGS instruments did not reveal any signa-

[2]SNR plasmas are often out of ionization equilibrium, due to a combination of a low density, n_e, and a short time, t, since the plasma was heated (i.e. the ionization age is $n_e t < 10^{12}$ cm^{-3} s).

tures of Fe-L emission (Vink et al. 2003). Abundance determinations of O, Ne, Mg, and Si are more reliable, as those lines are clearly visible in CCD spectra. So any low spectral resolution X-ray Fe abundance measurements of SN 1006 should be regarded with caution, especially since Fe is in an ionization stage (< Fe XVII), which produces almost no Fe-L emission. Another reason to distrust Fe abundance measurements in SN 1006 is that optical absorption spectra toward a bright UV background star reveals that the reverse shock has probably not yet reached the Fe-rich ejecta (Hamilton et al. 1997). SN 1006 is in that sense both dynamically and spectroscopically younger than Tycho's remnant, a result of its evolution in a low density environment.

This is the reason that in order to see all Fe one has to look at dynamically older remnants, in which the reverse shock has heated most of the ejecta. An excellent example is DEM L 71 (Hughes et al. 2003). *Chandra* images in the energy bands of O and Fe-L show that most of the O VII/VIII emission comes from a narrow shell, but most Fe-L line emission comes from the center of the remnant (Fig. 2). In fact, assuming that the plasma inside the shell consists of pure Fe, the estimated Fe mass is ~ 0.8 $M_\odot$ (Hughes et al. 2003; van der Heyden et al. 2003), consistent with Type Ia nucleosynthesis calculations. In general, assuming that a plasma consists of a pure metal plasma, with no or little H, will give rise to a lower overall mass estimate and a higher mass estimate for that particular metal. Critical to this calculation is the source of the exciting electrons. Although, most of the Fe ejecta seems to be shocked, DEM L 71 is less suitable for getting the overall ejecta abundances, as the outer C-O, and Si layers are likely to be mixed with the interstellar medium (ISM). Therefore, advances in our understanding of Type Ia SNe should probably come from combining studies of young and old Type Ia remnants.

2.2. Core-Collapse Remnants

Recently, the interest in core-collapse SNe has been fueled by the discovery that some gamma ray bursts (GRBs) are associated with Type Ic SNe (e.g., Stanek et al. 2003). As GRBs are likely to be caused by jets, it is possible that jet formation plays a role in less energetic SNe as well.

Of all the potential core-collapse remnant candidates, a special place is taken by the O-rich remnants, such as Cas A, Puppis A, G292.0+1.8, in the galaxy, N132D, 0540–69.3 in the LMC and 1E 0102.2–7219 in the SMC. The reason is that the O-yield increases with progenitor mass. O-rich remnants are therefore likely to be remnants of the most massive stars, with a main sequence (MS) mass in excess of 20 $M_\odot$. Those stars suffer considerable mass loss and end their lives as Wolf-Rayet (WR) stars. WR stars are probably progenitors of Type Ib/c SNe, and studying their remnants may reveal important information about the explosion properties of Type Ib/c stars. There is already considerable evidence for explosion asymmetries for 1E 0102.2–7219 (Flanagan et al. 2001) and Cas A.

Recently point sources have been found in some of these remnants: Cas A, Puppis A, 0540–69.3, and G292.0+1.8 (see Pavlov, Sanwal & Teter, these proceedings). The point source in G292.0+1.8 is a 136-ms radio pulsar (Camilo et al. 2002). This is of special interest for the black hole vs neutron star birth rate, as modeling of massive star evolution and explosion suggests that stars

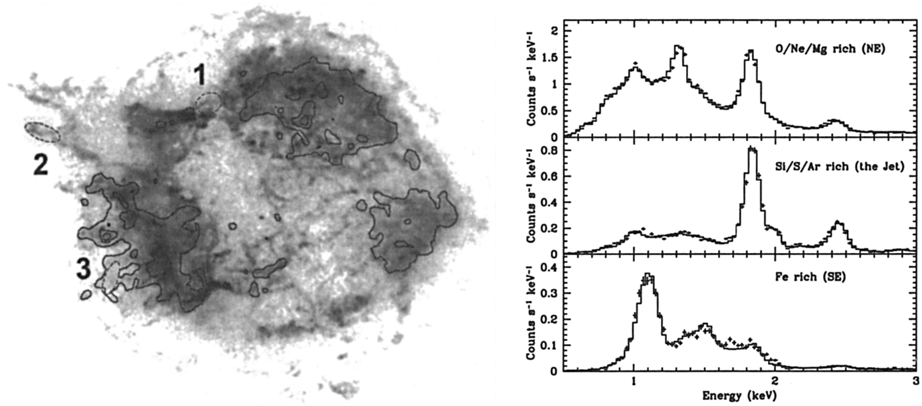

Figure 3. *Chandra* image of Cas A (left), in the Si-Heα band around 1.85 keV, with Fe-K ($\sim$6.7 keV) contours overlayed. *Chandra* spectra from different regions show the variety in elemental abundances (right).

with initial masses of 25–60 $M_\odot$ are likely to produce a black hole rather than a neutron star (Heger et al. 2003). This is in accordance with the mass estimate of Cas A indicating a 18–22 $M_\odot$ MS mass, but it is at odds with the presence of a pulsar in G292.0+1.8, which has been claimed to be the remnant of a 30–40 $M_\odot$ star (Gonzalez & Safi-Harb 2003).

The young remnant Cas A ($\sim$ 320 yr) is the best studied O-rich SNR (see Vink 2004a for a review). It has long been thought to be a Type Ib remnant from a WR star, as just a few optically emitting ejecta knots show hydrogen traces (Fesen, Becker & Blair 1987). However, circumstellar density and mass estimates suggest that Cas A's shock is plowing through a dense red supergiant wind, and not a much more tenuous WR wind. This either suggest that Cas A never reached the WR phase (Chevalier & Oishi 2003), or was only a WR star for a relatively short period (Laming & Hwang 2003). However, the presence of small amounts of hydrogen is not significant, as atmospheres of some late-type WR stars contain H. More important is that Cas A's progenitor must have suffered considerable mass loss, as mass estimates suggest an ejecta mass of 2–4 $M_\odot$, which should be compared to the high O-mass of $\sim$ 1–3 $M_\odot$ (Vink, Kaastra & Bleeker 1996), suggesting a MS mass of 18–25 $M_\odot$. Core collapse in such a compact star enhances the effects of explosion asymmetries and reduces the amount of fall-back. Both explosion asymmetries and reduced fall-back, together with a relatively high explosion energy of $\sim 2 \times 10^{51}$ ergs can explain the measured ^{44}Ti yield of $\sim 2 \times 10^{-4}$ $M_\odot$ (Iyudin et al. 1994; Vink et al. 2001), higher than model predictions (Woosley & Weaver 1995). ^{44}Ti is synthesized deep inside the supernova, and is a result of the α-rich freeze-out process (Arnett 1996). Recently Hwang & Laming (2003) have argued that this process is the source of Fe-rich knots outside Cas A's main shell. The Fe-rich knots are situated mostly in the southeast of the remnant (Fig. 3), and their position indicate initial velocities in excess of 4500 km s^{-1}, surprisingly high as this is material synthesized deep inside the SN. There is no evidence that the Fe-rich knots were ejected by jets,

https://doi.org/10.1017/S0074180900180581 Published online by Cambridge University Press

or has another simple geometry. On the contrary, redshifted Fe-rich material can be observed in X-ray Doppler maps, but is projected inside the northern part of the main shell (Willingale et al. 2002). Evidence for jet formation comes from Si-rich material. The protrusion in the East, known from optical images as "The Jet", is Si-rich. Comparing the Si-image with an Mg-image reveals a possible Si-rich counter jet that ran into denser material in the West (Vink 2004a). The nearly circular rim of X-ray continuum emission (Gotthelf et al. 2001), marking Cas A's forward shock, suggests that the circumstellar medium is reasonably spherically symmetric, and strengthens the idea that the explosion itself is responsible for the observed ejecta asymmetries.

Cas A suggests that core-collapse explosions cannot be assumed to be spherically symmetric. Whether asymmetries, and possible jet formation, are related to the GRB mechanism is not clear. The asymmetries in the Fe ejecta are probably related to the convective instabilities that have recently been found in simulations of core-collapse SNe (Kifonidis et al. 2003).

3. Supernova Remnants and Collisionless Shock Physics

Supernovae drive shock waves through the ISM that remain visible for tens of thousands of years in the form of SNRs. As the ISM is very tenuous, the particle mean free path is larger than the typical shock width. That a shock forms at all is due to the fact that heating occurs not through two body interaction, but due to the coupling of particles with self-generated plasma waves. These so-called collisionless shocks are interesting from a physical point of view, since the detailed shock heating process is unknown.

One question considering collisionless shocks is whether they heat each particle species according to its own Rankine-Hugoniot equation,[3] or whether different species quickly equilibrate through collisionless processes (i.e. $kT_{\rm e} = kT_{\rm H} = kT_{\rm He}$, etc). The first evidence for non-equilibration of temperatures was the equal Doppler width of H, C and O UV line emission from SN 1006, whereas thermal line broadening for equilibrated temperatures should give relative line widths inversely proportional to the particle mass (Laming et al. 1996). Other evidence came from modeling the width of Hα line emission in comparison with the narrow to broad line Hα ratio observed in a number of SNRs, which indicate that low Mach number shocks are fully equilibrated, whereas high Mach number shocks are not (Rakowski, et al. 2003). Finally, Vink et al. (2003) measured the O VII line width of a compact knot in SN 1006 with the *XMM-Newton* RGS, which indicates a high O VII temperature of $\sim 350 - 700$ keV compared to an electron temperature of ~ 1.5 keV.

One remaining question is whether the shock heating process always produces a Maxwellian particle distribution and what the influence is of CR acceleration on the temperature(s), as CRs provide an additional heat sink, or even lead to heat loss as a result of CR escape.

[3]This equation is $kT_i = 3/16 m_i v_s^2$, for high Mach number shocks and species i, without additional energy sinks, such as CR acceleration.

4. Cosmic Ray Acceleration in Supernova Remnants

In order to accelerate particles up to "the knee" of the CR spectrum by diffusive shock acceleration, the accelerating system needs to be larger than the gyro-radius of the particle at "the knee" energy. The only Galactic sources that satisfy this criterion are SNRs and magnetars. However, although SNRs are the most plausible sources for cosmic ray acceleration, there is no direct evidence that SNRs accelerate *ions* and that they are capable of accelerating them up to "the knee". For a long time the evidence for CR acceleration in SNRs was radio synchrotron emission from electrons with energies up to the GeV range. However, recent progress has been made, as *ASCA* observations of SN 1006 detected X-ray synchrotron emission, evidence for electron acceleration up to a maximum of 100 TeV (Koyama et al. 1995).

Although this considerably extends the range for which electron CRs are observed, the maximum energy range falls short of the "knee" energy. There can be two reasons for that: either the maximum electron energy is age limited, in which case also the maximum ion energy is too low, as ions and electrons are accelerated by the same process, which for relativistic energies only depend on particle energy, not on particle mass; or the maximum electron energy is determined by synchrotron or inverse Compton losses, in which case ions may well be accelerated up to, or even beyond "the knee".

Recently, Vink & Laming (2003) showed that Cas A's narrow X-ray continuum rim could be explained by assuming that it is caused by synchrotron radiation and that the rim width is determined by the synchrotron loss time (τ). As the plasma velocity behind the shock has a velocity $\frac{1}{4}v_s$, one can express the width as $\Delta r = \frac{1}{4}v_s\tau$.[4] τ depends on the particle energy and B-field as $\sim 1/B^2E$, but one can solve for E and B by using the the scaling of the observed photon energy as E^2B. This gives $E \sim 50$ TeV and $B \sim 10^{-4}$ G for the B-field close to Cas A's shock front, which is lower than the average magnetic field (> 0.5 mG; Vink & Laming 2003). The implication is that the maximum electron energy is determined by synchrotron losses, suggesting that the maximum ion CR energies may be higher. Moreover, the magnetic field near the shock front is higher than usually assumed, facilitating a more efficient CR shock acceleration.

A more direct proof of ion CR acceleration in SNRs has to wait for the unambiguous detection of pion decay in the TeV range with Cherenkov detectors. So far, a number of remnants, Cas A, SN 1006, and RX J1713.7–3946, have been detected in the TeV range, but definitive proof is lacking that the emission is due to pion decay, as inverse Compton emission from electrons provides a good alternative explanation (Vink 2004b, and references therein). However, this field is progressing rapidly, thanks to improved Cherenkov telescopes and future γ-ray missions like *GLAST*.

Acknowledgments. This work is supported by NASA's Chandra Postdoctoral Fellowship Award Nr. PF0-10011 issued by the Chandra X-ray Observatory Center, which is operated by the SAO under NASA contract NAS8-39073.

---

[4]This has interesting implications for the CR diffusion length scale; see Vink (2004b).

References

Arnett, D. 1996, Supernovae and Nucleosynthesis, (Princeton: PUP)

Bandiera, R. & van den Bergh, S. 1991, ApJ, 374, 186

Branch, D., et al. 1995, PASP, 107, 1019

Camilo, F., et al. 2002, ApJ, 567, L71

Chevalier, R. A. & Oishi, J. 2003, ApJ, 593, L23

Dyer, K. K. et al. 2001, ApJ, 551, 439

Fesen, R. A., Becker, R. H., & Blair, W. P. 1987, ApJ, 313, 378

Flanagan, K. A. et al. 2001, in AIP Conf. Ser., Vol. 565, Young Supernova Remnants, eds. S. Holt & U Hwang, (New York: AIP), p. 226

Gonzalez, M. & Safi-Harb, S. 2003, ApJ, 583, L91

Gotthelf, E. V. et al. 2001, ApJ, 552, L39

Hamilton, A. J. S., et al. 1997, ApJ, 481, 838

Heger, A., et al. 2003, ApJ, 591, 288

Hughes, J. P. et al. 1995, ApJ, 444, L81

Hughes, J., Ghavamian, P., Rakowski, C., & Slane, P. 2003, ApJ, 582, L95

Hwang, U., & Gotthelf, E. V. 1997, ApJ, 475, 665

Hwang, U., & Laming, J. M. 2003, ApJ, 597, 362

Iyudin, A. F. et al. 1994, A&A, 284, L1

Kifonidis, K., Plewa, T., Janka, H.-T., & Müller, E. 2003, A&A, 408, 621

Koyama, K. et al. 1995, Nature, 378, 255

Laming, J. M., & Hwang, U. 2003, ApJ, 597, 347

Laming, J. M., et al. 1996, ApJ, 472, 267

Long, K. S. et al. 2003, ApJ, 586, 1162

Nomoto, K. et al. 1997, Nucl. Phys. A, 621, 467

Pavlov, G. G., Zavlin, V. E., Sanwal, D., & Trümper, J. 2002, ApJ, 569, L95

Rakowski, C. E., Ghavamian, P., & Hughes, J. P. 2003, ApJ, 590, 846

Stanek, K. Z. et al. 2003, ApJ, 591, L17

Stephenson, F. R., & Green, D. A. 2002, Historical Supernovae and Their Remnants, (Oxford: Clarendon Press)

van der Heyden, K., Bleeker, J.., Kaastra, J., & Vink, J. 2003, A&A, 406, 141

Vink, J., Kaastra, J. S., & Bleeker, J. A. M. 1996, A&A, 307, L41

Vink, J. et al. 1999, A&A, 344, 289

— 2001, ApJ, 560, L79

— 2003, ApJ, 587, 31

Vink, J. & Laming, J. M. 2003, ApJ, 584, 758

Vink, J. 2004a, New Ast. Rev., 48, 61

— 2004b, Adv. Sp. Res., 33, 356

Willingale, R., et al. 2002, A&A, 381, 1039

Woosley, S. E. & Weaver, T. A. 1995, ApJS, 101, 181