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Review

Progress in multi-waveband observations of supernova remnants

Xuejuan Yang [a,b], Fangjun Lu [a], Wenwu Tian [c,d,*]

[a] Particle Astrophysics Center, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[b] Department of Astronomy, Beijing Normal University, Beijing 100875, China
[c] National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, CAS, Beijing 100012, China
[d] Department of Physics & Astronomy, University of Calgary, Alberta, Canada T2N 1N4

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Abstract

The development of observational techniques has enriched our knowledge of supernova remnants. In this paper, we review the main progresses in the last decade, including new discoveries of supernova remnants and the associated (rare type of) pulsars, nucleosynthesis, the interaction between supernova remnants and molecular clouds, dust in the supernova remnants, shock physics, and cosmic ray accelerations.

Keywords: Supernova remnant; Observations

1. Introduction

Massive stars usually end their lives with supernova (SN) explosions. The explosion can be so powerful that it outshines a galaxy at its peak with a total energy of $\sim 10^{44}$ J. The outer layers of the exploding star are ejected at supersonic speed, resulting in an outward blast wave. Meanwhile, the blast wave is decelerated as it expands into the interstellar medium (ISM), forming a reverse shock propagating inwards. The shocked materials, together with the stellar remnant (if existing), form a supernova remnant (SNR). SNRs are often very bright in the radio and X-ray bands, as the shocks can heat the ISM and ejecta to X-ray emitting temperature and accelerate electrons to produce synchrotron radiation in radio and/or even X-ray bands. The interaction between an SNR and the nearby molecular clouds (MCs) often trigger emissions of molecular lines. The optical emission of an SNR usually comes from shocked ejecta, while infrared emission traces the dust around. Polarization observations of SNRs have brought new insight into SNR physics [1].

Supernovae (SNe) are classified as types I and II based on the presence of hydrogen Balmer lines in their spectra at the maximum brightness, and each type has sub-types for different properties of spectra or lightcurves (Fig. 1 in Ref. [2]). It is widely accepted that SNe Ia corresponds to the thermonuclear disruption of a C–O dwarf in an accreting binary system after its mass appoaches the Chandrasekhar limit. SNe Ib/Ic and SNe II come from core-collapses of massive stars, giving birth to neutron stars for progenitor mass in the range of 9–25 M or black holes for more massive stars [3]. SNRs are important for understanding our Galaxy. They heat up the interstellar medium, distribute heavy elements throughout the Galaxy, and accelerate cosmic rays (CRs). The shock wave of an SN injects energy into the interstellar gas, compresses and accelerates it. SNR-MC interaction may trigger star formation. SNRs are also believed to be the dominant source of Galactic CRs. In the last decade, great progresses have been made in understanding SNRs, thanks to the new generation of telescopes.

* Corresponding author. Tel.: +86 10 64839807; fax: +86 10 64852055.
E-mail addresses: tww@bao.ac.cn, tww@iras.ucalgary.ca (W. Tian).

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2. Supernova explosion and physics

2.1. Discoveries of SNRs and pulsars associated

The discrepancy between the number of known Galactic SNRs ($\sim$270) and that predicted by theory ($\geqslant$1000) has been considered as the result of the selection effects in current sensitivity-limited radio surveys. This is supported by the discoveries of many new SNRs and candidates in recent surveys with high sensitivity and spatial resolution at low radio frequencies [4–6]. Some individual SNRs have newly been discovered from multi-band observations, e.g. Tian et al. [7] by radio observations, Stupar et al. [8] by optical observations, and Funk et al. [9] by X-ray observations.

In addition to the expanding parts of SNRs, some core-collapse SN explosions produce pulsars too. Discoveries of pulsars in SNRs are therefore clues to the classification of the SNe associated. Up to now more than 50 pulsars have been claimed to be likely associated with the SNRs [10,11]. New generation of X-ray space observatories, e.g. XMM-Newton and Chandra X-ray observatories have shown their power in detecting X-ray pulsars. With its sub-second spatial resolution, Chandra has confirmed pulsars in core-collapse SNRs G292.0 + 1.8 [12], G54.1 + 0.3 [13], G21.5-0.9 [14] and discovered pulsar wind nebula candidates in N23 [15], G15.9 + 0.2 [16] and DA 530 [17].

One of the most exciting progresses in pulsars is the discoveries of "anomalous X-ray pulsars" (AXPs) and "soft γ-ray repeaters" (SGRs), which have very different properties from traditional radio pulsars. AXPs and SGRs cannot be powered by the rotational energy or by accretion of matter from a binary companion star, and have extremely high surface magnetic fields ($B > 10^{14}$G, the "magnetars", see Ref. [18] for a review). Some AXPs and SGRs are associated with SNRs, such as Kes 73/AXP 1E 1841-045; G29.6 + 0.1/AX J1845-0258; CTB 109/AXP 1E 2259 + 586, and N49/SGR 0526-66 [19,20]. The compact object in the center of Cassiopiea A (Cas A) might also be a magnetar [21].

The association between SNRs and AXPs/SGRs could be used to constrain the properties of AXPs/SGRs. Vink and Kuiper [22] investigated the explosion energies of three SNRs (Kes 73, CTB 109 and N49) hosting AXPs/SGRs. They found that the energies of these SNRs are close to those of normal SNe and favor the possibility that magnetars descend from progenitors with high magnetic field cores instead of rapidly rotating proto-neutron stars [22]. However, this was argued against by the 50% higher explosion energy of Kes 73 [23], which implies either a larger magnetic field decay rate in the magnetar model or a larger accretion rate in the accretion-based models. More high-resolution multi-waveband observations of the AXPs/SGRs-related SNRs will help to constrain their properties, and distinguish different theoretical models.

2.2. Nucleosynthesis

Numerical calculations [24,25] predict that the nucleosynthesis during the SN explosion is in "onion" layers with dominant elements ordered in shells following their atomic number.

In young SNRs, the element stratification might be reserved because of the relatively short time of interaction with the surroundings. A good icon is the Tycho's SNR. X-ray observations show that Fe K line peaks at a much smaller radius than that of Si, S and Fe L [26,27]. Hwang et al. [26] found that the Fe K emission in Tycho is from an isolated component with ionization age of 100 times smaller than that of Si or S, implying that Fe ejecta may retain some stratification and be located at the inner layers and therefore be reversely shocked more recently. X-ray spectroscopy of G292.0 + 1.8 shows that there is little evidence of metal (Si, S and Fe) enriched ejecta from explosive nucleosynthesis, suggesting that the ejecta are strongly stratified by composition and that the reverse shock has not propagated to the Si/S- or Fe-rich zones [28].

However, such stratification could be destroyed during the explosion in some cases. For Cas A, the Fe-rich ejecta is located at larger radius than that of Si [29,30]. It is concluded that the ejecta has undergone a spatial inversion, which might be caused by the neutrino-driven convection initiating core-collapse [29].

Numerical models have also calculated the nucleosynthesis yield as a function of progenitor mass [24,25]. By comparing the abundance pattern from both observations and theoretical calculations, the progenitor mass can be estimated [31]. However, the observational results basically come from the spectra fitting with plasma models, which only take into account of the relatively abundant elements that show strong emission lines in the spectra. As the sensitivity of the detectors increases, some new emission lines have been detected, such as Cr and Mn [32,33], which are not included in any available plasma model. Since these elements have been included in numerical calculations, it will be helpful to constrain the properties of the SNe/SNRs by including them in the plasma models.

3. SNRs and their environment

3.1. Interaction with molecular clouds

Core-collapse SN explosions are expected to occur in MCs, since their massive progenitors ($\geqslant 8M_{\odot}$) are born in MCs and their lifetimes ($\leqslant 3 \times 10^7$ years) are often shorter than the typical lifetime of an MC [34]. As the SNRs expand, they might interact with MCs.

The first clear evidence for this interaction is from IC443 based on observations of shocked CO [35] and OH [36] emissions. Such kind of studies became more intense after the realization of OH 1720 MHz maser line emission as a "signpost" of the interaction [37] (see Ref. [38] for a review). Surveys have been done [39–41] and several SNRs have been found with such maser emissions, including W28, W44, 3C391, etc. These SNRs are mostly mixed-morphology SNRs, which have been suggested to be strongly associated with the OH 1720 MHz maser emission [42,43]. It is predicted that the OH 1720 MHz line will switch off at large OH column density (N_{OH}), and the 6049 MHz and 4765 MHz lines will be on instead, with a peak N_{OH} of $3 \times 10^{17}\ cm^{-2}$ and of several times higher, respectively [44,45]. These lines may serve as a complementary signal of warm, shocked gas when the OH column density is large.

The emission lines from CO, H_2 or other molecules in the shocked gas can also trace such interaction. Using these emission line diagnosis, interactions are identified in G347.3 − 0.5 [46] and HB21 [47], etc.

A direct way to identify the interaction is to determine the distances to SNR and MC systems. Based on a new distance-measurement method (Tian-Leahy method by the HI and CO observations), Tian et al. [48] suggested the interaction between SNR G18.8 + 0.3 and a molecular cloud, and a measured distance of ~12 kpc to the SNR/CO cloud system. A more reliable example is the SNR W41/HESS 1834-087/molecular cloud system. High-precision distance measurements to the system support that the SNR is physically associated with the giant molecular clouds. Therefore, the SNR/cloud interaction leads to the TeV γ-ray emission in the cloud material [49]. The method is so powerful that recently it is used to solve the intriguing puzzle on the distance to SNR Kes 75/PWN J1846-0258 system [50]. It is worth applying this distance-measurement method to more claimed SNR/could system so that we could refine current models of SNR/cloud interaction.

3.2. Dust in SNRs

It has been discovered that there is a huge amount of dust (10^8–$10^9\ M_\odot$) in very high redshift ($z > 6$) galaxies and quasars [51,52], corresponding to the Universe age of 700 million years. The stellar winds at the late stages of evolution of the stars are thought to be the main sources of dust in galaxies, but they are not able to produce that much in such a short time [53]. Type II SNe could be potential sources, with a dust production of 0.08–1 $M_\odot$ in the ejecta per SN, varying with metallicity and progenitor mass [54].

Dunne et al. [55] report a detection of cold dust of 2–4 $M_\odot$ in Cas A. They imply that SNe are at least as important as stellar winds in producing dust in our Galaxy and could have been the dominant source of dust at high redshift [55]. The optical and mid-infrared observations of SN 2003gd show a total dust amount of 0.02 $M_\odot$, suggesting that SNe might be the major dust factories [56]. However, it is also argued that the dust detected in Cas A may originate from interstellar dust in a molecular cloud complex located in the line of sight between the Earth and the SNR [57]. The Spitzer observations show that the dust mass in SN 2003gd is only about $4 \times 10^{-5}\ M_\odot$, arguing against the presence of 0.02 $M_\odot$ newly formed dust in the ejecta [58]. Recently Rho et al. [59] presented a comprehensive analysis of the dust mass in Cas A with the Spitzer observations, which shows that the total dust mass is sufficient to explain the lower limit of the dust mass in high redshift galaxies. However, what is the real total amount of dust in the ejecta of core-collapse SNe remains an open question, and further research is required.

4. Shock physics

4.1. Electron–ion temperature equilibrium

The shocks in SNRs are often referred to as collisionless shocks, because the particle collision length scale is much larger than the typical size of the shock structure. Although the nature of electron and ion heating behind collisionless shocks in SNRs remains an open question, a number of observational advances have provided more information about it.

Behind the collisionless shock there can exist a population of cold neutral ions that are not affected by the shock passage. Some of them might be collisionally excited before being destroyed by collisional ionization or charge transfer. They will emit narrow Hα and Hβ Balmer lines with widths representing the pre-shock temperatures. Those having charge exchange with shock heated protons will produce broad Balmer lines, whose widths will be given by the temperature of postshock protons. In this case, the broad-to-narrow line ratio can be used to measure the electron–proton temperature ratio (T_e/T_p), which shows the degree of equilibration. By observations and theoretical studies of the Cygnus Loop, RCW 86 and Tycho based on this method, Ghavamian et al. [60] obtain the equilibration degree of electron/proton temperatures. However, the narrow Balmer lines might be contaminated by emissions from a shock precursor, leading to a higher modeled broad-to-narrow ratio, such as for DEM L71 [61]. In such cases, the electron temperature can be determined from the X-ray bremsstrahlung emission instead [61,62].

Using the high spectral resolution data from the XMM-Newton observations, Vink et al. [63] found a 3.4 eV broadening of O emission line in SN 1006, implying an O temperature of 530 ± 150 keV. The electron temperature from the same observation is about 1.5 keV, suggesting a low degree of equilibration in this remnant. This is consistent with the optical [64] and ultraviolet [65] studies. Rakowski [66] compiled each method that has been used to measure the equilibration and every SNR on which they have been tested. A negative correlation between the degree of equilibration and the shock velocity is found [66]. Such correlation was further studied by Ghavamian et al. [67]. They found a relationship $(T_e/T_p)_0 \propto v_s^2$ in good agreement with the observations, where $(T_e/T_p)_0$ represents the electron-proton temperature equilibration at the shock front and v_s is the shock velocity. Although such a relationship has been suggested, many questions remain: What mechanism causes the sharp decrease of temperature equilibrium at small shock speed? Does this relationship hold for collisionless shocks in fully ionized gas? Progress in this developing field depends on accurate modeling of the emission from pre-shock and post-shock gases, as well as evidence from multiple wave-bands, and useful assessments of the cosmic ray production and its effect on the shock.

4.2. Cosmic-ray acceleration

SNRs are believed to be the dominant source of Galactic CRs, at least for energies up to the "knee" of the CR spectrum (3×10^{15} eV). The radio synchrotron emission from the shocks of shell-type SNRs has provided direct evidence for accelerated electrons with energies up to the GeV range. It was increased to 10–100 TeV after the first detection of X-ray synchrotron filament in SN1006 [68]. Such filament have also been detected in Cas A, RCW 86, Tycho, Kepler, G266.2-1.2, G347.3-0.5, etc (see also Ref. [69]).

With the development of atmospheric Cerenkov detectors (H.E.S.S, CANGROO series, etc), we are able to image SNRs by TeV γ-ray observations, which play an important role in tracing the CR acceleration in SNRs. γ-ray emissions are detected in several SNRs, including RX J1713.7-3946, RX J0852.0-4622, G0.9+0.1, W41, etc. (see Ref. [70] for an H.E.S.S observation review). However, the H.E.S.S observations on SN1006 have no detection of TeV γ-ray emission from any compact or extended region associated with the remnant [71]. Using the observed X-ray flux and γ-ray upper limit, they get a lower limit on the post-shock magnetic field of $B > 25\ \mu$G [71].

Various models have been established to explain the overall spectra of nonthermal emission (from radio up to TeV γ-ray) in SNRs. These models can basically be categorized as the time-dependent and steady ones. Zhang's group [72,73] modeled the non-thermal emission from old and young SNRs under time-dependent frame. These models are applied to the observations of SNRs, and can well represent their multiwavelength spectra.

Although there is much observational evidence for electron acceleration in SNRs, that for proton (dominant component of CRs) acceleration is rare. One example is RX J1713.7-3946, where pions (π°) decay (the signature of proton acceleration) was detected [74].

The amplification of magnetic field is potentially the key for accelerating protons and heavier ions up to the "knee" of the CR spectrum [75,76]. The X-ray synchrotron filaments provide not only evidence of CR acceleration, but also information of the magnetic field at the shock front. Based on the width of the filaments, Vink et al. [77] estimated the magnetic field strength of 0.08–0.16 mG at the shock front of Cas A, much higher than the Galactic average value ($\sim 3\ \mu$G). X-ray filaments in SN1006 [78], Tycho [79] and Kepler [80] indicate similar magnetic field strength in these remnants, which might be evidence for CR induced magnetic field amplification [69]. Uchiyama et al. [76] reported the discovery of the brightening and decay of X-ray hot spots in RX J1713.7-3946 on a one-year timescale, which might imply that we have witnessed the ongoing shock-acceleration of electrons in real time. They conclude that the rapid variability showing the origin of X-rays is the synchrotron emission of ultrarelativistic electrons, meanwhile the electron acceleration occurs in a strong magnetic field with an amplification factor of more than 100 [76].

5. Summary and prospectives

In this paper, we have reviewed recent progress in the study of SNRs from multi-band observations. More SNRs and (rare type of) pulsars associated are discovered. Using the high spatial and energy resolution data of SNRs, we are able to study the nucleosynthesis process during stellar evolution and SN explosion, and also the interaction between SNRs and their surroundings. From the perfect laboratory of shock physics, we know more about the collisionless shock in SNRs, such as the electron-ion equilibration after shock passage and the cosmic-ray acceleration.

Nevertheless, many open questions remain. From example, the known basic parameters of many SNRs, such as the distances and ages, have large uncertainty. High-precision measurements to these parameters are very important to study not only the SNRs themselves, but also the related pulsars, molecular clouds and so on. This depends on further advances in both observational techniques and measurement methods. By comparing the abundance pattern of SNRs with numerical calculations, some information of the SN explosions could be obtained, such as the explosion type and progenitor mass. However, current theoretical calculations are generally over-simplified with respect to the real SN explosions, and thus cannot match all the observations. Meanwhile, plasma models including elements such as Cr and Mn are required. AXPs/SGRs have been suggested to be neutron stars with very strong magnetic fields ("magnetars"). Are they and high magnetic field radio pulsars different phases of a more uniform class of object? What is their evolutionary sequence? Why are the spin periods of AXPs/SGRs strongly clustered at 5–12 s? To answer these questions, it is necessary to enlarge the sample of this rare type of pulsars and make high-precision observations. SNR shocks can accelerate CRs, but how efficient is the acceleration? What is the maximum energy that shocks can be accelerated to? How strong is the magnetic field? Is it amplified or just compressed? If the amplification exists, what is the mechanism? The new generation of telescopes will shed new light on these issues.

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References

[1] Xu JW, Han JL, Sun XH, et al. Polarization observations of SNR G156.2+5.7. Astron Astrophys 2007;470:969–75.
[2] Vink J. A review of X-ray observations of supernova remnants. Nucl Phys B Proc Suppl 2004;132:21–30.
[3] Heger A, Fryer CL, Woosley SE, et al. How massive single stars end their life. Astrophys J 2003;591:288–300.
[4] Helfand DJ, Becker RH, White RL, et al. MAGPIS: a multi-array Galactic plane imaging survey. Astron J 2006;131:2525–37.
[5] Brogan CL, Gelfand JD, Gaensler BM, et al. Discovery of 35 new supernova remnants in the inner Galaxy. Astrophys J 2006;639:L25–9.
[6] Kothes R, Uyanlker B, Reid RI. Two new Perseus arm supernova remnants discovered in the Canadian galactic plane survey. Astron Astrophys 2005;444:871–81.
[7] Tian WW, Leahy DA, Haverkorn M, et al. Discovery of the radio and X-ray counterpart of TeV γ-ray source HESS J1731-347. Astrophys J 2008;679:L85–8.
[8] Stupar M, Parker QA, Filipović MD. G315.1+2.7: a new Galactic supernova remnant from the AAO/UKST H α survey. Mon Not Roy Astron Soc 2007;374:1441–8.
[9] Funk S, Hinton JA, Moriguchi Y, et al. XMM-Newton observations of HESS J1813-178 reveal a composite supernova remnant. Astron Astrophys 2007;470:249–57.
[10] Tian WW, Haverkorn M, Zhang HY. Characteristics of the supernova remnant G351.7+0.8 and a distance argument against its association with PSR J1721-3532. Mon Not Roy Astron Soc 2007;378:1283–6.
[11] Tian WW, Leahy DA. The radio SNR G65.1+0.6 and its associated pulsar J1957+2831. Astron Astrophys 2006;455:1053–8.
[12] Hughes JP, Slane PO, Park S, et al. An X-ray pulsar in the oxygen-rich supernova remnant G292.0+1.8. Astrophys J 2003;591:L39–42.
[13] Lu FJ, Wang QD, Aschenbach B, et al. Chandra observation of supernova remnant G54.1+0.3: a close cousin of the Crab nebula. Astrophys J 2002;568:L49–52.
[14] Camilo F, Ransom SM, Gaensler BM, et al. PSR J1833-1034: discovery of the central young pulsar in the supernova remnant G21.5-0.9. Astrophys J 2006;637:456–65.
[15] Hayato A, Bamba A, Tamagawa T, et al. Discovery of a compact X-ray source in the LMC supernova remnant N23 with Chandra. Astrophys J 2006;653:280–4.
[16] Reynolds SP, Borkowski KJ, Hwang U, et al. A new young Galactic supernova remnant containing a compact object: G15.9+0.2. Astrophys J 2006;652:L45–8.
[17] Jiang B, Chen Y, Wang QD. Chandra view of DA 530: a sub-energetic supernova remnant with a pulsar wind nebula? Astrophys J 2007;670:1142–8.
[18] Woods PM, Thompson C. Soft γ-ray repeaters and anomalous X-ray pulsars: magnetar candidates. In: Compact stellar X-ray sources. Cambridge, UK: Cambridge University Press; 2006. p. 547–86.
[19] Gaensler BM, Slane PO, Gotthelf EV, et al. Anomalous X-ray pulsars and soft γ-ray repeaters in supernova remnants. Astrophys J 2001;559:963–72.
[20] Gaensler BM. Anomalous X-ray pulsars and soft gamma-ray repeaters – the connection with supernova remnants. Adv Space Res 2004;33:645–53.
[21] Krause O, Rieke GH, Birkmann SM, et al. Infrared echoes near the supernova remnant Cassiopeia A. Nature 2005;308:1604–6.
[22] Vink J, Kuiper L. Supernova remnant energetics and magnetars: no evidence in favour of millisecond proto-neutron stars. Mon Not Roy Astron Soc 2006;370:14–8.
[23] Tian WW, Leahy DA. The distance and age of the SNR Kes 73 and AXP 1E 1841-045. Astrophys J 2008;677:292–6.
[24] Woosley SE, Weaver TA. The evolution and explosion of massive stars. II: Explosive hydrodynamics and nucleosynthesis. Astrophys J 1995;101:181–235.
[25] Thielemann FK, Nomoto K, Hashimoto M. Core-collapse supernovae and their ejecta. Astrophys J 1996;460:408–36.
[26] Hwang U, Gotthelf EV. X-ray emission-line imaging and spectroscopy of Tycho's supernova remnant. Astrophys J 1997;475:665–82.
[27] Decourchelle A, Sauvageot JL, Audard M, et al. XMM-Newton observation of the Tycho supernova remnant. Astrophys J 2001;365:218–24.
[28] Park S, Hughes JP, Slane PO, et al. Nucleosynthesis in the oxygen-rich supernova remnant G292.0+1.8 from Chandra X-ray spectroscopy. Astrophys J 2004;602:L33–6.
[29] Hughes JP, Rakowski CE, Burrows DN, et al. Nucleosynthesis and mixing in Cassiopeia A. Astrophys J 2000;528:L109–13.
[30] Willingale R, Bleeker JAM, van der Heyden KJ, et al. X-ray spectral imaging and doppler mapping of Cassiopeia A. Astron Astrophys 2002;381:1039–48.
[31] Ganzalez M, Safi-Harb S. New constraints on the energetics, progenitor mass, and age of the supernova remnant G292.0+1.8 containing PSR J1124-5916. Astrophys J 2003;583:L91–4.
[32] Hwang U, Petre P, Hughes JP. The X-ray line emission from the supernova remnant W49B. Astrophys J 2000;532:970–9.
[33] Miceli M, Decourchelle A, Ballet J. The X-ray emission of the supernova remnant W49B observed with XMM-Newton. Astron Astrophys 2006;453:567–78.
[34] Chevalier RA. Supernova remnants in molecular clouds. In: Young supernova remnants: eleventh astrophysics conference. Maryland, USA. Oct. 16–18; 2001. p. 109–118.
[35] DeNoyer LK. Discovery of shocked CO within a supernova remnant. Astrophys J 1979;232:L165–8.
[36] DeNoyer LK, Shocked OH. Within a supernova remnant. Astrophys J 1979;228:L41–3.
[37] Frail DA, Goss WM, Slysh VI. Shock-excited maser emission from the supernova remnant W28. Astrophys J 1994;424:L111–3.
[38] Wardle M, Yusef-Zadeh F. Supernova remnant OH masers: signposts of cosmic collision. Science 2002;296:2350–4.
[39] Frail DA, Goss WM, Reynoso EM, et al. A survey for OH(1720 MHz) maser emission toward supernova remnants. Astron J 1996;111:1651–9.
[40] Green AJ, Frail DA, Goss WM, et al. Continuation of a survey of OH (1720 MHz) maser emission towards supernova remnants. Astron J 1997;114:2058–67.
[41] Koralesky B, Frail DA, Goss WM, et al. Shock-excited maser emission from supernova remnants: G32.8-0.1, G337.8-0.1, G346.6-0.2, and the HB 3/W3 complex. Astron J 1998;116:1323–31.
[42] Yusef-Zadeh F, Wardle M, Rho J, et al. OH (1720MHz) masers and mixed-morphology supernova semnants. Astrophys J 2003;585:319–23.
[43] Chen Y, Su Y, Slane PO, et al. A Chandra ACIS view of the thermal composite supernova remnant 3C 391. Astrophys J 2004;616:885–94.
[44] Wardle M. Collisional excitation of OH (6049 MHz) masers in supernova remnant-molecular cloud interactions. In: Proceedings of the International Astronomical Union, Australia; 2007. p. 336–337 [March 12–16].
[45] Pihlström YM, Fish VL, Sjouwerman LO, et al. Excited-state OH masers and supernova remnants. Astrophys J 2008;676:371–7.
[46] Moriguchi Y, Tamura K, Tawara Y, et al. A detailed study of molecular clouds toward the TeV γ-ray supernova remnant G3473-0.5. Astrophys J 2005;631:947–63.
[47] Byun D, Koo B, Tatematsu K, et al. Interaction between the supernova remnant HB 21 and molecular clouds. Astrophys J 2006;637:283–95.
[48] Tian WW, Leahy DA, Wang QD. Radio and X-ray images of the SNR G18.8 + 0.3 interacting with molecular clouds. Astron Astrophys 2007;474:541–7.
[49] Tian WW, Li Z, Leahy D, et al. VLA and XMM-Newton observations of the SNR W41/TeV γ-ray source HESS J1834-087. Astrophys J 2007;657:L25–8.
[50] Leahy DA, Tian WW. The distances of the SNR Kes 75 and PWN J1846-0258 system. Astron Astrophys 2008;480:L25–8.

[51] Isaak KG, Priddey RS, McMahon RG, et al. The SCUBA bright quasar survey (SBQS): 850-μm observations of the z>4 sample. Mon Not Roy Astron Soc 2002;329:149–62.
[52] Bertoldi F, Carilli CL, Cox P, et al. Dust emission from the most distant quasars. Astron Astrophys 2003;406:55–8.
[53] Dwek E. The evolution of the elemental abundances in the gas and dust phases of the Galaxy. Astrophys J 1998;501:643–65.
[54] Todini P, Ferrara A. Dust formation in primordial Type II supernovae. Mon Not Roy Astron Soc 2001;325:726–36.
[55] Dunne L, Eales S, Ivison R, et al. Type II supernovae as a significant source of interstellar dust. Nature 2003;424:285–7.
[56] Sugerman BEK, Ercolano B, Barlow MJ, et al. Massive-star supernovae as major dust factories. Science 2006;313:196–200.
[57] Krause O, Birkmann SM, Rieke GH, et al. No cold dust within the supernova remnant Cassiopeia A. Nature 2004;432:596–8.
[58] Meikle WPS, Mattila S, Pastorello A, et al. A Spitzer space telescope study of SN 2003gd: still no direct evidence that core-collapse supernovae are major dust factories. Astrophys J 2007;665:608–17.
[59] Rho J, Kozasa T, Reach WT, et al. Freshly formed dust in the Cassiopeia A supernova remnant as revealed by the Spitzer space telescope. Astrophys J 2008;673:271–82.
[60] Ghavamian P, Raymond J, Smith RC, et al. Balmer-dominated spectra of nonradiative shocks in the Cygnus Loop, RCW 86, and Tycho supernova remnants. Astrophys J 2001;547:995–1009.
[61] Ghavamian P, Rakowski CE, Hughes JP, et al. The physics of supernova blast waves. I. kinematics of DEM L71 in the large Magellanic cloud. Astrophys J 2003;590:833–45.
[62] Rakowski CE, Ghavamian P, Hughes JP. The physics of supernova remnant blast waves. II. Electron–ion equilibration in DEM L71 in the large Magellanic cloud. Astrophys J 2003;590:846–57.
[63] Vink J, Laming JM, Gu MF, et al. The slow temperature equilibration behind the shock front of SN 1006. Astrophys J 2003;587:31–4.
[64] Ghavamian P, Winkler PF, Raymond JC, et al. The optical spectrum of the SN 1006 supernova remnant revisited. Astrophys J 2002;572:888–96.
[65] Laming JM, Raymond JC, McLaughlin BM, et al. Electron-ion equilibration in nonradiative shocks associated with SN 1006. Astrophys J 1996;472:267–74.
[66] Rakowski CE. Electron ion temperature equilibration at collisionless shocks in supernova remnants. Adv Space Res 2005;35:1017–26.
[67] Ghavamian P, Laming JM, Rakowski CE. A physical relationship between electron-proton temperature equilibration and Mach number in fast collisionless shocks. Astrophys J 2007;654:69–72.
[68] Koyama K, Petre R, Gotthelf EV, et al. Evidence for shock acceleration of high-energy electrons in the supernova remnant SN 1006. Nature 1995;378:255–8.
[69] Vink J. Non-thermal X-ray emission from supernova remnants. In: X-ray diagnostics of astrophysical plasma: theory, experiment, and observation. Massachusetts, USA; 2004. p. 160-6. [Nov. 15–17].
[70] Rowell G, H.E.S.S collaboration. Galactic TeV γ-ray sources: a summary of H.E.S.S observations. J Physics 2006;47:21–30.
[71] Aharonian FA, Akhperjanian AG, Bazer-Bachi AR, et al. Upper limits to the SN1006 multi-TeV gamma-ray flux from HESS observations. Astron Astrophys 2005;437:135–9.
[72] Fang J, Zhang L. Non-thermal emission from old supernova remnants. Mon Not Roy Astron Soc 2008;384:1119–28.
[73] Zhang L, Fang J. Hadronic contributions for TeV γ-ray emission from young supernova remnants. Astrophys J 2007;666:247–60.
[74] Enomoto R, Tanimori T, Naito T, et al. The acceleration of cosmic-ray protons in the supernova remnant RX J1713.7-3946. Nature 2002;416:823–6.
[75] Ballet J. X-ray synchrotron emission from supernova remnants. Mon Not Roy Astron Soc 2006;37:1902–8.
[76] Uchiyama Y, Aharonian FA, Tanaka T, et al. Extremely fast acceleration of cosmic rays in a supernova remnant. Nature 2007;449:576–8.
[77] Vink J, Laming JM. On the magnetic fields and particle acceleration in Cassiopeia A. Astrophys J 2003;584:758–69.
[78] Bamba A, Yamazaki R, Ueno M, et al. Small-scale structure of the SN 1006 shock with Chandra observations. Astrophys J 2003;589:827–37.
[79] Hwang U, Decourchelle A, Holt SS, et al. Thermal and nonthermal X-ray emission from the forward shock in Tycho's supernova remnant. Astrophys J 2002;581:1101–15.
[80] Cassam-Chenai G, Decourchelle A, Ballet J, et al. XMM-Newton observation of Kepler's supernova remnant. Astron Astrophys 2004;414:545–58.