Progress on multi-waveband observations of supernova remnants

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Abstract

A number of observational advances have increased our knowledge about supernova remnants. In this paper we review the main progresses made in the last decade, including new discoveries of supernova remnants and the associated 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

Massive stars usually end their lives with supernova (SN) explosions. It’s very powerful, with total energy of \( \sim 10^{44} \text{J} \), to outshine a galaxy at peak. 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 expanding into the interstellar medium (ISM), forming a reverse shock propagating inwards. The shocked materials, along with the stellar remnant (if exist) form a supernova remnant (SNR). SNRs are often very bright in the radio and X-ray bands, as the shocks often heat the ISM and ejecta to X-ray emitting temperature and accelerate the 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 emission of molecular lines. The optical emission of an SNR often comes from shocked ejecta, while infrared emission traces the dust around. The polarization observations of SNRs bring new insight to SNR physics\textsuperscript{1}.

The SNe are classified as type I and II based on the presence of Hydrogen Balmer lines in their spectra at maximum brightness or not, and each type has sub-types for different properties of spectra or lightcurves (c.f Fig. 1 in Ref\textsuperscript{2}). It’s widely accepted that SNe Ia correspond to the thermonuclear disruption of a C-O dwarf in an accreting binary system after its mass approaches Chandrasekar limit. SN Ib/Ic and SNe II are from core collapses of massive stars, giving birth to neutron stars for progenitor mass in the range of \( 9M_\odot \sim 25M_\odot \) or black holes for more massive stars\textsuperscript{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. The interaction between an SNR and molecular clouds 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.

1 Supernova explosion and physics

1.1 Discoveries of SNRs and pulsars associated

This discrepancy between the number of known Galactic SNRs (\( \sim 270 \)) and that predicted by theory ( \( \geq 1000 \)) has been considered as the result of the selection effects in the current sensitivity-limited radio surveys. This is supported by the discoveries of many new SNRs and candidates in the recent surveys with high sensitivity and spatial resolution at low radio frequencies\textsuperscript{4,5,6}. Some individual SNRs have newly

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been discovered from multi-band observations, e.g. Tian et al.\cite{7} by radio observations, Stupar et al.\cite{8} by optical observations, and Funk et al.\cite{9} by X-ray observations.

In addition to the expanding SNRs, some core-collapse SN explosions also produce pulsars. Discoveries of pulsars in SNRs are therefore clues for the classification of the SNe associated. Up to now more than 50 pulsars have been claimed to be likely associated with the SNRs\cite{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 discovered pulsars in core-collapse SNRs G292.0+1.8\cite{12}, G54.1+0.3\cite{13}, G21.5-0.9\cite{14} and pulsar wind nebula candidates in N23\cite{15}, G15.9+0.2\cite{16} and DA 530\cite{17}.

One of the most exciting progresses about pulsars is the discoveries of “Anomalous X-ray Pulsars” (AXPs) and “Soft $\gamma$-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\cite{18} for a review). Some AXPs and SGRs are associated with SNRs, e.g. Kes 73/AXP 1E 1841-045, G29.6+0.1/AX J1845-0258, CTB 109/AXP 1E 2259+586, N49/SGR 0526-66 etc\cite{19,20}. The compact object in the center of Cassiopeia A (Cas A) might also be a magnetar\cite{21}. The newest exciting discovery is from the Fermi Gamma Ray Space Telescope which detects a $\gamma$-ray pulsation, i.e. first $\gamma$-ray-only pulsar with a period of 316.86 ms, near the center of SNR CTA 1\cite{22}.

The association between SNRs and AXPs/SGRs could be used to constrain the properties of AXPs/SGRs. Vink & Kuiper\cite{23} investigated the explosion energies of three SNRs (Kes 73, CTB 109 and N49) hosting AXPs/SGRs. They found that these SNRs’ energies 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\cite{23}. However, this was argued against by the 50% higher explosion energy of Kes 73\cite{24}, which implies either a larger magnetic field decay rate in the magnetar model or a larger accretion rate in accretion-based models. The more high-resolution multi-waveband observations of the AXPs/SGRs-related SNRs will help to constrain their properties, and distinguish from different theoretical models.

1.2 Nucleosynthesis

Numerical calculations\cite{25,26} predict that the nucleosynthesis during SN explosion is in onion type with dominant elements ordered in shells following their atomic number.

In young SNRs, the element stratification might be reserved since the relatively short time of interaction with surroundings. A good icon is the Tycho’s SNR. X-ray observations show that Fe K line peaks at a much smaller radius than those of Si, S and Fe L\cite{27,28}. Hwang et al.\cite{27} find that the Fe K emission in Tycho is from an isolated component with ionization age 100 times smaller than that of Si or S, implying that Fe ejecta may retain some stratification and be located at the inner layers thus reverse shocked more recently. X-ray spectroscopy of G292.0+1.8 shows that it has 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\cite{29}.

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\cite{30,31}. It is concluded that the ejecta has undergone a spatial inversion, which might be caused by the neutrino-driven convection initiating core-collapse\cite{30}.

The numerical models have also calculated the nucleosynthesis yield as a function of progenitor mass\cite{25,26}. By comparing the abundance pattern from both observations and theoretical calculations, the progenitor mass can be estimated\cite{32}. However, the observational results basically come from the spectra fitting with plasma models, which only contain the relatively abundant elements that show strong emission lines in the spectra. As the increase of the sensitivity of the detectors, some new emission lines have been detected, such Cr, Mn and etc\cite{33,34}, which are not included in all the available plasma models. Since these elements have been included in the numerical calculations, it will be helpful to constrain the properties of the SNe/SNRs including them in the plasma models.
2 SNRs and their environment

2.1 Interaction with molecular clouds

Core collapse SN explosions are expected to occur in MCs, since their massive progenitors (≥ 8M⊙) are born in MCs and their lifetimes (≤ 3 × 10⁷ years) are often shorter than the typical lifetime of an MC. 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 and OH emission. Such study became more intense after the realization of OH 1720 MHz maser line emission as a “signpost” of the interaction (see Ref[39] for a review). Surveys have been done [40, 41] and [42] and several SNRs have been found with such maser emission, 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 line. 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 x 10^{17} cm⁻², and of several times higher, respectively [43] and [44]. These lines may serve as a complementary signal of warm, shocked gas when the OH column density is large.

Such interaction can also be traced by the shocked emission lines from CO, H₂ or other molecules. Using these diagnosis, interactions are identified in G347.3-0.5 [47] and HB21 [48] etc. The direct way to identify the interaction is to determine the distances to an SNR and MC system. Based on a new distance-measurement method (Tian-Leahy method by the HI and CO observations), Tian et al. [49] suggest the interaction between SNR G18.8+0.3 and a molecular cloud, and give a 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 so the SNR/cloud interaction leads to the TeV γ-ray emission in the cloud material [50]. The method is so powerful that an intriguing puzzle on the distance to SNR Kes 75/PWN J1846-0258 system has been solved recently [51]. It is worth determining distances to more claimed SNR/cloud systems by this method so that we could refine current models of SNR/cloud interaction.

2.2 Dust in SNRs

It has been discovered that there is a huge amount of dust (10^⁸ ~ 10^⁹ M⊙) in very high redshifted (z > 6) galaxies and quasars [52, 53], corresponding to the Universe age of 700 million years. The stellar winds at the late time 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 [54]. Type II SNe are potential sources, with a dust production of 0.08 ~ 1M⊙ in the ejecta per SN, varying with metallicity and progenitor mass [55].

Dunne et al. [56] report a detection of cold dust of ~ 2 x 10⁻⁴ M⊙ in Cas A. They imply that SNe are at least as important as stellar wind in producing dust in our Galaxy and would have been the dominate source of dust at high redshift [56]. The optical and mid-infrared observations of SN 2003gd show a total dust amount of 0.02 M⊙, suggesting that SNe might be major dust factories [57]. However, it is then 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 [58]. The Spitzer observations show that the dust mass in SN 2003gd is only about 4 x 10⁻⁵ M⊙, arguing against the presence of 0.02 M⊙ of newly formed dust in the ejecta [59]. Recently Rho et al. [60] present a comprehensive analysis of the dust mass in Cas A with the Spitzer observations and show that the total dust mass is sufficient to explain the lower limit of the dust mass in high redshift galaxies. It still remains an open question what’s the real total amount of dust in the ejecta of core collapse SNe, and more investigations are required.

3 Shock physics

3.1 Electron-Ion temperature equilibrium

The shocks in SNRs are often referred to as collisionless shocks as 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 increased our knowledge 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 by the shock passage. Some of them might be collisionally excited before being destroyed by collisional

our knowledge about it.

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 gas, as well as evidence from multiple wave-bands, and useful assessments of the cosmic ray production and its effect on the shock.

3.2 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 × 1015 eV). The radio synchrotron emission at the shocks of shell-type SNRs has provided direct evidence for accelerated electrons with energies up to GeV range. It was raised to 10 ~ 100 TeV after the first detection of X-ray synchrotron filament in SN1006. Such filaments have also been detected in Cas A, RCW 86, Tycho, Kepler, G266.2-1.2, G347.3-0.5 etc (see also Ref[70]).

As the development of atmospheric Cerenkov detectors (H.E.S.S, CANGROO series etc), it is able to image SNRs by TeV γ-ray observations, which play an important role to trace 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[71] for a H.E.S.S observation review). However, the H.E.S.S observations to SN1006 have no detection of TeV γ-ray emission from any compact or extended region associated with the remnant. Using the observed X-ray flux and γ-ray upper limit, they get a lower limit on the post-shock magnetic field of $B > 25 \mu G$.\[80\]

Various models have been established to account for the overall spectra of nonthermal emission (from radio up to TeV γ-ray) in SNRs, which can basically categorized as time-dependent and steady ones. Fang et al.\[89\] and Zhang et al.\[84\] model the non-thermal emission from old and young supernova remnants under time-dependent frame respectively. These models are applied to the observations of SNRs, and can well represent their multi-wavelength spectra.

Although there is a lot of observational evidences for electron acceleration in SNRs, that for proton (dominate component of CRs) acceleration is rare. One example is RX J1713.7-3946, where pions ($\pi^0$) decay (the signature of proton acceleration) was detected.\[82\]

The amplification of magnetic field is potentially the key for accelerating protons and heavier ions up to the “knee” of the CR spectrum.\[80, 82\] 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.\[82\] estimated the magnetic field strength to be $0.08 - 0.16 m G$ at the shock front of Cas A, much higher than the Galactic average value ($\sim 3 \mu G$). X-ray filaments in SN1006, Tycho,\[82\] etc (see Ref[81] for a H.E.S.S observation review). However, the H.E.S.S observations to SN1006 have no detection of TeV γ-ray emission from any compact or extended region associated with the remnant.\[82\] Using the observed X-ray flux and γ-ray upper limit, they get a lower limit on the post-shock magnetic field of $B > 25 \mu G$.\[80\]
and Kepler indicate similar magnetic field strength in these remnants, which might be evidence for CR induced magnetic field amplification. Uchiyama et al. report 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 shows the origin of X-rays to be synchrotron emission of ultrarelativistic electrons, meanwhile the electron acceleration occurs in a strong magnetic field with an amplification factor of more than 100.

4 Summary and prospectives

In this paper, we review the progresses 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. As a 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, there are still many open questions. The known basic parameters of many SNRs, such as the distances and ages, have large uncertainty. High-precision measurement to these parameters, however, 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. Although it’s widely believed that SN Ia is from the thermonuclear explosion of a white dwarf, is the explosion mechanism accretion single degenerate or double degenerate? Is the explosion a detonation (supersonic), deflagration (subsonic), or is there transition from deflagration to detonation? By comparing the abundance pattern of SNRs with numerical calculations, some information of the SN explosions has been given, such as the explosion type, progenitor mass. However, the current theoretical calculations are generally simplified with respect to the real SN explosions, and thus often cannot match all the observations. Meanwhile, as the discovery of emission lines from less abundant elements, such as Cr or Mn, plasma models which includes these elements would be required. AXPs/SGRs have been suggested to be neutron stars with very strong magnetic fields (“magnetars”). Do 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 would be helpful to enlarge the sample of this rare type of pulsars and make high-precision observations. SNR shocks can accelerate CRs. But how efficient the acceleration is? What is the maximum energy shocks can accelerated to? How strong is the magnetic field? Is it amplified or just compressed? If the amplification exists, what’s the mechanism? The new generation of telescopes will shed new light on these issues.

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