SUPERNOVA REMNANTS

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In the past few years, a number of new observations of galactic supernova remnants (SNRs) in radio, optical and X-ray domains have become available. About 150 radio sources have been classified as galactic SNRs. Of these, only for four SNRs, the Crab, Tycho, Kepler, SN 1006 and possibly for 3C58, the supernova events have been documented historically. The main observable features of the SNRs often differ from remnant to remnant. The non-thermal radio source is assumed to be common to all remnants; some may have optical nebulosity, X-ray emission and pulsar associated with them. Only two SNRs, Crab and Vela-X, exhibit all the above four features. But there is little doubt that all the listed SNRs belong to the same class of objects. SNRs and related topics have been discussed in detail in a recent review article by Woltjer (1972) and in the proceedings of the international conferences on " Crab Nebula " (1972) " Interstellar Gas Dynamics " (1970) and " Supernovae and Supernova Remnants " (1973). In this review, we present a summary of the recent developments in the study of SNRs.

EVOLUTION OF A SUPERNOVA REMNANT:

The evolution of a supernova remnant can be schematically divided into four stages (Woltjer 1970). The outer envelope of the star ejected during the supernova explosion acts as a massive piston moving supersonically through the surrounding interstellar medium and forms a shell preceded by a shock front: (i) in the earliest stage, the ejected material expands undecelerated until the mass of the swept up interstellar material is comparable to the ejected mass of the supernova; (ii) when the swept up mass is large, the expansion slows down and is adiabatic as long as the radiative losses are negligible; (iii) when the radiative losses become significant, the pressure forces are no longer important and the shell expands at constant radial momentum; (iv) finally, when the expansion slows down to the random motions of the surrounding interstellar medium, the SNR loses its identity and merges with the interstellar medium. Numerical computation of the physical conditions in the remnant shell as a function of its age have been made by several authors (Gull 1973; Rosenberg and Scheuer 1973; Mansfield and Salpeter 1974). In the early stage, the radio emission is probably turned on by the Rayleigh—Taylor instability at the outer edge of expanding ejecta. In old remnants, the radio emission appears to be due to internally generated relativistic electrons and cosmic ray electrons in the presence of the interstellar magnetic field, which has been amplified by compression behind the shock front. The optically seen filaments are formed due to thermal instabilities occurring in regions of the shell as the hot gas behind the shock begins to cool. The X-rays from SNR seem to be mostly the thermal emission from the hot plasma behind the shock front.

OPTICAL OBSERVATIONS:

Twentyfive SNRs have been observed optically as emission nebulae and they show a wide variety of structures such as: (a) incomplete shell outlined by very sharp filaments, e.g., the Cygnus loop; (b) mass of long looping filaments, e.g., Vela-X, S1947; (c) shell containing a few sharp filaments and a number of more diffuse filaments, e.g., HB9; (d) filled with filamentary nebulosity, e.g., W28. The Crab nebula is unique with a system of filaments emitting line radiation and an amorphous component emitting synchrotron radiation. The γ-Cyg nebula is also unique as it shows no filamentary structure (Bergh et al 1973). Expansion of the filaments have been observed in 11 SNRs and are in the range 5500 km/sec for the youngest remnant Cas A and 22 km/sec for the older remnant HB 21.

Recently, Mathewson and Clarke (1972) have used the relatively high ratio of (S II)/H_α in optical nebulae as an excellent criterion to identify SNRs optically from H II regions (Mathewson and Clarke 1972).

RADIO OBSERVATIONS:

A series of new high resolution observations of intensity and polarization in a number of SNRs has been made recently, e.g., Willis (1973), Velusamy and Kundu (1974a), Dickel and Milne (1974), Clark et al (1973). All SNRs except a few like the Crab Nebula and 3C58 show radio brightness distributions suggestive of a shell structure. However, large deviations from a perfect spherical shell source are seen in most of them. Many have only partial shells; some have low intensity extensions in some directions; many do not show any spherical symmetry. The observed structures may be consequences of the assymmetries in the supernova explosion and also due to the inhomogeneity of the surrounding interstellar medium into which the remnant shell is expanding. High resolution radio observations show very sharp boundaries coinciding with that of the optical nebulosities. Also very good spatial coincidence between optical filaments and radio ridges have been observed (e.g., in the Cygnus loop and IC443). Radio observations with resolutions better than 1′ arc suggest very thin remnant shells in many cases. For example, the lunar occultation observation of IC443 with resolution better than 30″ arc at Ooty suggests a very thin shell for some parts of the remnant with a thickness of only 1/15 of the shell radius (Gopalkrishna 1974). In such cases, the contribution from the swept up interstellar cosmic ray electrons and fields to the observed radio emission may be very significant. Some older remnants (e.g., HB3, HB9) seem to have very thick shells. An expanding H I shell has been observed around the supernova remnant HB21 (Assousa and Erkes 1973).

The projected magnetic field patterns in the old SNRs appear to be tangential to the brightness distributions. The magnetic fields in these remnant shells are believed to be the ambient interstellar fields amplified by the compression at the expanding shock front. The young shell sources (Cas A, Tycho, SN1006) show radial magnetic field patterns and are consistent with the field amplification by convective motions in their remnant shells. 3C58 has brightness distribution similar to the Crab nebula and seems to have uniform field pattern with field lines oriented along its major axis (e.g., Velusamy 1973; Kundu and Velusamy 1972; Dickel and Milne 1973).

The evolution of an expanding shell source emitting synchrotron radiation suggests a relationship between the source surface brightness (Σ) and its linear diameter (D). Mathewson and Clarke (1973) have obtained a relation

$$\Sigma_{408} = 10^{-15}\, D^{-3}\ \mathrm{W\ m^{-2}\ Hz^{-1}\ Sr^{-1}} \tag{1}$$

using mostly the identified SNR in the Large Megellanic Cloud (LMC) for which distances are known reliably and a few galactic ones. However, there appears to be a difference between the SNR in the LMC and those in the Galaxy; namely, the diameters of the galactic objects are about 15 per cent less than those of the same surface brightness in the LMC. Recently, Clark et al (1973) have suggested

$$\Sigma_{408} = 7 \times 10^{-16}\, D^{-3}\ \mathrm{W\ m^{-2}\ Hz^{-1}\ Sr^{-1}} \tag{2}$$

for the galactic SNR. The relationship ($\Sigma \sim D^{-3}$) is also consistent with the magnetic field strength and the total number of relativistic electrons in the remnant shell remaining constant with the expansion and the energy of relativistic electrons changing only by the expansion. The distances of the SNR, derived using the Σ—D relation, are not very dependable as the intrinsic differences between individual SNRs are large.

About 14 supernova remnants have been detected so far in the Magellanic clouds. Weak, variable radio emission has been detected from the remnant associated with the supernova 1970g in the external galaxy M101 (Goss et al 1973). Continued observations of this remnant in M101 would throw much light on the evolution of radio emission from SNRs at very early stages. Attempts to detect radio emission from remnants of known supernovae in other external galaxies have proved to be unsuccessful (De Bruyn 1973).

X-RAY OBSERVATIONS:

Supernova remnants were the first class of X-ray sources to be recognised as such. X-ray emission has been detected from about 12 SNRs and north polar spur (NPS). The young remnants emit at energies > 2 kev while the older remnants primarily emit soft X-rays (energies < 1 kev). The detection of X-rays from NPS supports the view of NPS as a SNR. The spectrum, polarization and brightness distribution of X-ray emission in the Crab nebula has been well studied. At very high energies, the emission is confined to the region close to the pulsar. The emission from the Crab is non-thermal and is due to synchrotron radiation from high energy electrons produced by the central pulsar. All the other remnants including Cas A (the youngest SNR) and Vela-X (although there is a central pulsar in it) have only thermal X-ray emission. The two dimensional brightness distributions of Cas A, the Cygnus Loop, Vela-X and Puppis A are now available. Cas A shows a shell structure as in the radio (Fabin et al 1973). In the Cygnus Loop, the region of the X-ray emission coincides in the optical filaments. Also the line emission from O VII, O VIII and Fe XIV has been observed, confirming the thermal origin of the X-ray emission. A strong variable emission has been observed near the centre of the Loop.

The blast wave model for the thermal emission of X-rays from the hot plasma at temperatures $\sim 10^6$-10^7 °K behind the expanding shock of the remnants seems to be quite adequate. However, the velocity of shock to cause the required temperature seems to be much higher than the expansion velocities inferred optically from the filaments (e.g., the Cygnus Loop, IC443). Therefore, ages of the remnants inferred from X-rays are consistently lower than those obtained optically and by radio. But the differences could be resolved if the expansion velocity of shock is larger than those of filaments in the shell or if the density gradients in surrounding interstellar medium are taken into account.

PULSARS AND SNRs:

About five SNRs (the Crab, Vela-X, IC443, the Crux, HB21) are known to have pulsars associated with them. The newly discovered Ooty Pulsar $1911+03$ is only 0.8° away from the edge of W50 and their association is an interesting possibility (Mohanty and Balasubramanian 1974). Pulsar CP1919 seems to be associated with the galactic source G. 57.7+3.4. In most cases, the estimated ages of the pulsar and the remnants do not seem to be quite compatible, pulsar age always being higher than that of the remnant. The searches for old supernova remnants in the directions of many pulsars have proved to be unsuccessful (Schonhardt 1973; Velusamy and Kundu 1974b). Since the ages of most pulsars are over 10^6 years, their associated remnants would have already merged with the interstellar medium, losing their identity. However, we might still expect some continuum sources to be associated with pulsars as the halos or ghost remnants, as suggested by Blandford et al (1973). In these halos, the relativistic electrons accelerated by the pulsar emit synchrotron radiation in the interstellar fields. The pulsars CP1919+21, 0329+54, 2303+30 may be having such halos around them (Velusamy and Kundu 1974b).

DISTRIBUTION OF SNRs:

Ilovaisky and Lequeux (1972) find a scale height of 90 pc above the galactic plane for the SNR, similar to that of Population I objects. Therefore, majority of the SNRs must be of type II supernovae. Recently, Becker, and Kundu (1974) have found a possible correlation between the radio spectral index (α) and the height above the plane (z), with $\bar{z} \sim 120$ pc for $0.0 > \alpha > -0.4$ and

$z \sim 60$ pc for $-0.45 > \alpha > -0.65$. They find also that SNRs associated with the pulsars have flat spectral index and large z distance and that they may belong to type I supernovae. The most likely frequency of occurence of supernovae in the Galaxy seems to be 2 per century. The estimated total energy of the supernova is of the order of $10^{49} \sim 10^{50}$ ergs. However the above statistics of SNRs need to be further confirmed with more reliable distance estimates to individual remnants.

CONCLUSION :

Many theoretical problems, such as the origin and evolution of magnetic fields, and energetic particles, particularly with type of power law spectrum observed in supernova remnants are still not fully understood. To understand fully the energetics and evolution of the individual remnants, reliable estimates of their distance and the physical conditions in the surrounding interstellar medium are required. The high resolution (better than 30″) and high sensitivity observations of intensity and polarization in a number of SNRs being carried out at Westerbork and other observatories are very encouraging. Similarly, high resolution observations in X-rays would be highly desirable as the X-ray data seem to be complimentary to the optical and radio.

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