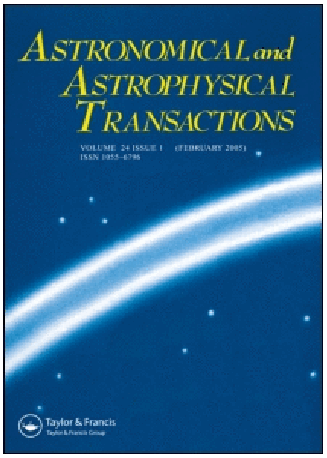

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SUPERNOVA REMNANTS AND THEIR NEUTRON STARS

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Both plerionic and composite supernova remnants with interior pulsars show a great variety of interactions between the pulsar and the surrounding remnant. Those objects without detected pulsars show the same kinds of characteristics and are otherwise indistinguishable from those in which the pulsar is seen. Other shell SNRs show interior cooling neutron stars or pulsars but no apparent connection between the shells and the neutron stars. A large range of progenitor characteristics and circumstellar environments must be needed to produce the differences among these supernova remnants.

KEY WORDS ISM: SNRs, pulsars, neutron stars

1 INTRODUCTION

It is thought that the explosion of a massive star as a supernova should produce both a supernova remnant (SNR) from the interaction of the ejecta with the surrounding medium and a collapsed neutron star in the core. The neutron star should also stimulate its near surroundings to produce a plerion, a compact nebula showing non-thermal synchrotron radiation at radio through x-ray wavelengths. Thus SNRs produced by high-mass stars should be composite remnants with an expanding shell and a plerion with a pulsar. In reality, we observe at least four kinds of SNRs associated with massive star explosions: pure plerions, composites, pure shells with non-pulsing cooling neutron stars, and some pure shells with apparent pulsars inside but no plerion.

We often see no apparent association between the SNR and a neutron star. In many other cases, the interaction of these components can have peculiar characteristics. We will present some of the properties of these four classes of SNR-neutron star relationships which show evidence for stimulation by a pulsar and some of which don't. Even within these separate classes there is a great variety among individual objects. We shall discuss some interesting examples and suggest possible explanations of some of the unusual features observed.

2 THE VARIETY OF SNR – NEUTRON STAR ASSOCIATIONS

2.1 Plerions

Plerions are filled SNRs with polarized synchrotron radiation presumably produced by injection of particles from the interior pulsar. Sometimes the central pulsar is readily detected, e.g. the Crab Nebula with a 33 ms pulsar (Staelin and Reifenstein, 1968), but in others there is no indication of a central compact object, e.g. MSH 15–57, the largest plerion known with a diameter of 25 pc (Gaensler *et al.*, 2000; Hughes *et al.*, 2000). Intermediate cases also exist. For example, 3C58 (Edge *et al.* 1959) has a small-diameter x-ray source in the center but no detectable pulsations (Helfand *et al.*, 1995).

Most plerions are rather elliptical with axial ratios of about 2/1. This ellipicity is probably related to the injection process which may not be isotropic. For example, the Chandra image of the region of the pulsar in the Crab Nebula shows a ring with apparent jets perpendicular to the plane of the ring (Chandra, 1999).

The radio spectra of the continuum synchrotron radiation from plerions is nearly flat with a break in the infrared to steeper values in the x-ray. This characteristic is generally attributed to synchrotron losses at the higher energies, but it is difficult to fit with uniform energy losses throughout the entire source. Simple losses should result in a kink in the energy spectrum of the radiating particles with a change by a power of 1.0, resulting in a change of 0.5 in the spectral index of the emission (Reynolds and Chevalier, 1984) . This change will generally occur in the infrared range of the spectrum for remnants with ages between a few hundred and a few thousand years. Most observed plerions, however, have steeper changes, such as 3C58 with a break of 0.7 (Green and Scheuer, 1992) suggesting time variations in the injection, acceleration rates, and initial energy spectra of the particles. Although accurate infrared flux densities are few, most of the spectra of the integrated emission from these SNRs show that the spectral breaks are not sharp but have some curvature (e.g. Gallant and Tuffs, 1999). A curved interface between two line segments would be found for a collection of sharp breaks over a range of particle energies in different locations within the remnant.

2.2 Composite SNRs

Composite SNRs contain internal plerions with the usual characteristics described above but also have extended shells with standard steeper spectrum radio synchrotron emission and thermal x-rays generated by shock heating from the supersonic expansion into the surrounding medium. The prototype of the composite SNRs is MSH 15–56 (Mills *et al.*, 1961) with a large filamentary radio and optical

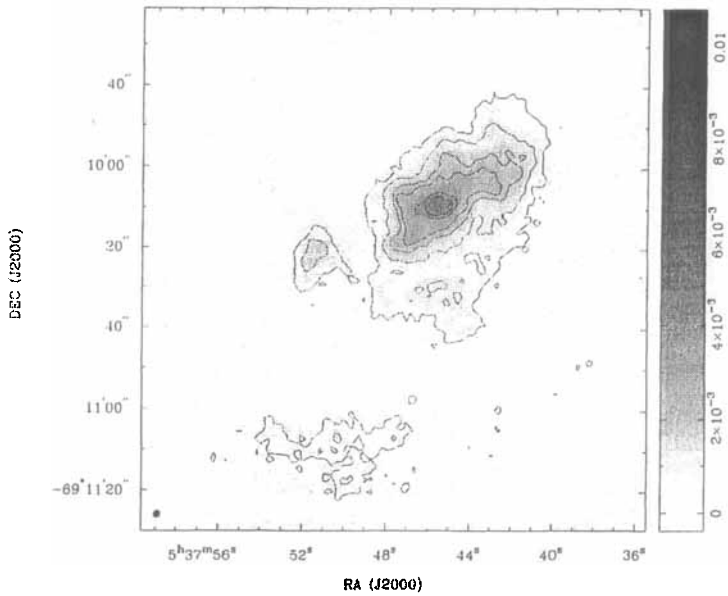

Figure 1 Radio image of N157B at a wavelength of 3 cm. The dot in the lower left corner represents the half power beamwidth.

shell over 40 pc across (e.g. Dickel *et al.*, 2000; van den Bergh, 1979). The radio plerion is offset from the center of the remnant by about 8 pc in a direction approximately perpendicular to the long axis of the plerion. The plerion also has an unusual striated appearance with the magnetic field directed along the striations. There are soft x-rays across the entire shell SNR, but the most interesting x-ray feature, is a small though definitely extended hard x-ray spot beyond one corner of the radio plerion (Plucinsky, 1998). No pulsar or point x-ray source has been detected anywhere in the remnant. Perhaps MSH 15-56 is an older version of N157B, discussed next.

The remnant N157B (Henize, 1956) in the LMC is an example of a SNR apparently just entering the composite stage. There is a hint of shell structure in the high-resolution radio images (see Figure 1 from Lazendic *et al.*, 2000), and a significant component of thermal emission in the x-ray radiation from this source (Dennerl *et al.*, 2001). The brightest part of the radio plerion is offset northward from both the center of the outline of the entire remnant and from the (also non-central) position of the 16-ms pulsar (Gotthelf *et al.*, 1998). The x-ray plerion is brightest right around the pulsar and then appears to trail off toward the brightest part of the radio emission as seen in Figure 2 (Wang *et al.*, 2001). It looks as if the pulsar began its life at the centroid of the radio feature and has moved off to the southeast by about 5 parsecs. This would infer a motion of about 1000 km s^{-1} for the estimated age of 5000 years. The decrease of x-ray emission away from the pulsar could be attributed to synchrotron losses of this high energy component while

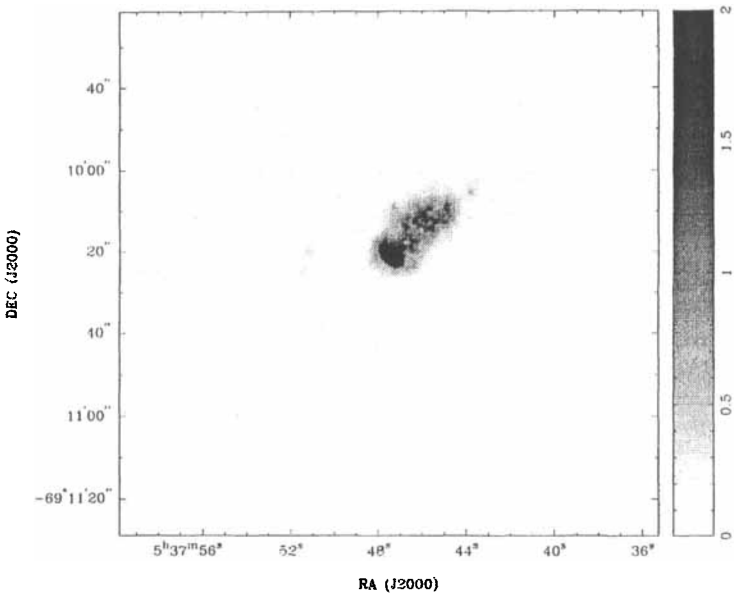

Figure 2 Chandra x-ray image of N157B. The greyscale only goes to 2 counts but the pulsar exceeds 30 counts.

the radio emission has not yet decayed. There should still be bright radio emission from the region just around the pulsar, however, which is not visible. Perhaps a high magnetic-field pulsar (a magnetar) might die quickly, so that the current emission from the near surroundings of the plerion could still be visible in x-rays but be too faint to see in the radio.

A differently appearing composite SNR is G21.5-0.9 which consists of a somewhat elliptical plerion with an x-ray half-width along the major axis of about 40″ and a near point x-ray peak in the center. The radio half-width in the same direction is 70″ (Bock *et al.*, 2000). Around this bright plerion is a faint (about 2% of the plerion brightness) x-ray ring with some shell characteristics; it extends to about 4 plerion diameters (Chandra, 2000; Bandiera, 2000). A radio shell at this brightness level would be difficult to detect in the available data. Radio images of G21.5-0.9 appear essentially identical at 5, 22, and 94 GHz (Bock *et al.*, 2000), suggesting that the break frequency in the synchrotron radiation spectrum may lie above the previously suggested value of 50 GHz (Salter *et al.*, 1989).

There are several other notable examples of composite SNRs. SS433 (Stephenson and Sanduleak, 1977) in W50 (Westerhout, 1956) is a binary system with helical jets and an extended shell SNR (e.g. Crampton *et al.*, 1980; Hjellming and Johnston, 1981; Downes *et al.*, 1981; Safi-Harb *et al.*, 1997). CTB 80 (Wilson and Bolton, 1960) has a pulsar, a plerion, a bright emission plateau, and multiple unexplained jets emanating from the central region of the SNR (Strom, 1988; Angerhofer *et al.*, 1981). The Vela SNR also has its pulsar offset from the plerion (Bock *et al.*,

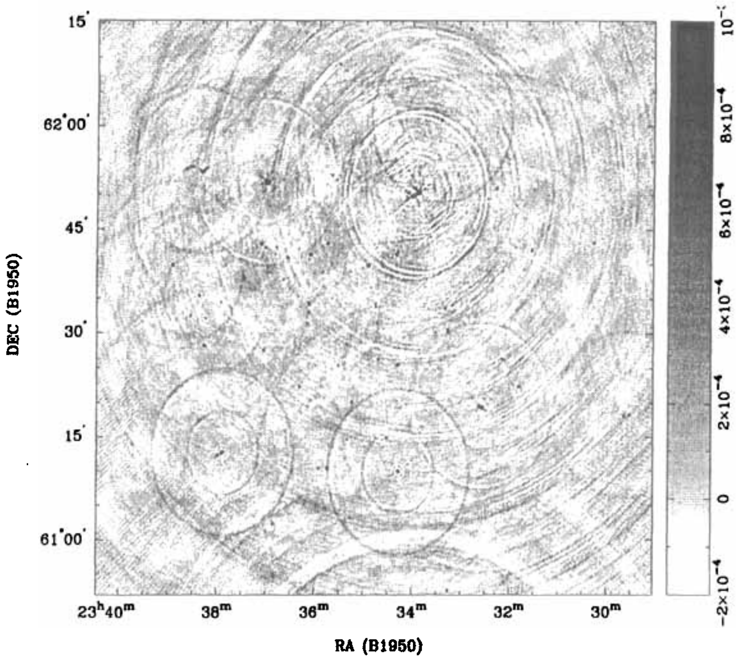

Figure 3 Westerbork 1380 MHz image of the center of G114.3+0.3 with a resolution of 15 arcsec.

1996). In W44, the plerion is barely distinguishable, being the smallest and faintest known plerion relative to its shell (Giacani *et al.*, 1997). Kes75 (Kesteven 1968) is a good example of a composite SNR containing an anomalous x-ray pulsar with a strong magnetic field and no radio pulses (Gotthelf *et al.*, 2000). The object 0540-693 in the LMC contains a pulsar, plerion, and a shell visible at all wavelengths (Manchester *et al.*, 1993; Gotthelf and Wang, 2000).

Thus, with the possible exception of 0540-693, all composite SNRs seem to have some unusual asymmetries between the pulsar and the plerion and/or irregular shell components which have yet to be understood. In addition there are often anomalous differences in the detection of the pulsar in different energy bands.

2.3 Shell SNRs with Quiescent Neutron Stars

Several SNRs appear to be normal shell remnants but they contain an isolated point x-ray source near the center. It is generally assumed that the x-ray sources are cooling neutron stars. There is no indication of any radio emission from or around these stars and no optical identifications have been found. The prototype of these objects is RCW103 (Rodgers *et al.*, 1961), a nearly circular shell SNR with an age of about 2000 years (Carter *et al.*, 1997) and a point x-ray source, 1E 161348−5055, at the very center (Tuohy and Garmire, 1980). No radio plerion component nor any relation of the x-ray source to the shell is found (Dickel *et al.*, 1996). The spectrum of the x-ray source appears to be that of a blackbody but there are fluctuations in the total x-ray flux of more than an order of magnitude over timescales of weeks to years (Gotthelf *et al.*, 1999). Recently, a 6-hour periodicity has been found in the x-ray emission (Garmire *et al.*, 2000) suggesting a possible binary system.

Cas A is the most prominent SNR to contain an interior neutron star as revealed in the first image released from the Chandra x-ray satellite (Chandra, 1999). There is no hint of excess radio emission at the location of the x-ray source (e.g. Braun *et al.*, 1987). The supernova is thought to have exploded from a massive supergiant star (Lamb, 1978) about 320 years ago so it is much too young for any plerionic emission to have decayed. Another oxygen-rich SNR, Puppis A, also contains an unidentified cooling neutron star (Petre *et al.*, 1996) It may be similar to Cas A, although older.

A final example of an isolated neutron star inside a shell SNR is 1E 1207.4−5209 within G296.5+10 (Mereghetti *et al.*, 1996). In this case, the SNR appears to be very old and barrel shaped. The x-ray spectrum is that of a blackbody but the emission is weak and only what would be expected from about 3% of the area of a neutron star.

Perhaps all of the members this class of cooling neutron stars might be in binary systems which could quench the pulsar-feeding of a plerion, and possible mass transfer or eclipses might sometimes block out some of the x-ray emission.

2.4 Shell SNRs with Pulsars but no Plerions

Fuerst *et al.* (1993) and Kulkarni *et al.* (1993) independently associated the pulsar PSR2334+61 (Dewey *et al.*, 1988) with the old, extended SNR G114.3+0.3. The spindown age of the pulsar is about 40,000 years and the distances of the two objects, while very uncertain, could be the same. Thus, they could be related. The image of the entire SNR (Fuerst *et al.*, 1993) shows an extended shell, more than 1° across with some smooth emission in the center but no specific emission at the pulsar position. The brightest feature on their image is an H II region, S165 (Sharpless, 1959) located within the area of the SNR at B1950 $23^h37.5^m$ and 61°38′. A short image of the central region of this SNR made with only one array configuration of the Westerbork Synthesis Radio Telescope is shown in Figure 3. There are many point sources and their diffraction patterns are present. Faint emission is seen from from S165 but the extended shell is too faint to detect. The pulsar is the southern point of the double source in the center of the image at $23^h34^m45^s$ and 61°34′25″. There is no sign of any compact emission component around it. As a pulsar ages, its injection into a plerion can decrease but it is difficult to understand why the original relativistic electrons are not still providing synchrotron emission at radio wavelengths after only tens of thousands of years. We cannot conclude whether the pulsar never stimulated a plerion, the plerion's emission died quickly, or we are viewing a chance superposition.

3 DISCUSSION

In principle all plerions should eventually become composites when the ejecta have swept up enough surrounding material to provide shock heating and particle acceleration. While we don't know the density of the local environment around all plerions, there are definite cases, such as G74.9+1.2 (Wallace *et al.*, 1997a) and G63.7+1.1 (Wallace *et al.*, 1997b), in which a naked plerion is observed to be within and/or interacting with dense circumstellar and interstellar media. Thus, they should have shells but don't. The authors argue that the pure plerions may arise from supernovae with less energy than those which produce composites or pure shell SNRs. We also note that as pulsars age, the plerions may fade before the shells.

In summary, while the plerionic and composite SNRs are considered to be powered by pulsars, many show no direct evidence of the pulsar or its specific effects on the SNR. Those with observed interactions between the pulsar and the SNR have a great variety of conditions. The shell SNRs without plerions sometimes have cooling neutron stars or even pulsars but no apparent relation between the SNR and the neutron star. Explanations of the differences can include differences in the surroundings caused by the pre-supernova evolution of the progenitor and its neighbors, a range of magnetic field strengths in the pulsars, different explosion energies, and possible membership in a binary system. The latter condition may account for rapidly moving pulsars, precessing or other irregular jet morphology, and perhaps the hiding of the pulsar and/or plerion.

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