X-RAY OBSERVATIONS OF CRAB-LIKE SUPERNOVA REMNANTS

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Abstract

On the basis of extensive radio surveys of the galactic plane, approximately 140 sources of diffuse radio emission have been classified as supernova remnants (SNR). Using spectral index and spatial distribution as the primary selection criteria, these have been subdivided into two groups, "shell" and "Crab-like". In each case, the radio emission is assumed to be of non-thermal origin. The two distinct morphologies arise from two distinct energy sources. For shell remnants, the energy is drawn from the reservoir of kinetic energy in the expanding shock front; in Crab-like remnants, the energy is drawn from the rotational kinetic energy of a central stellar remnant.

These two classes of remnants differ significantly in their x-ray emission. With few exceptions, radio shell remnants emit thermal x-rays from shock heated gas which is itself distributed in a shell. Crab-like sources (as defined by their radio properties) emit synchrotron x-rays in a centrally-peaked spatial distribution. Presumably, the x-ray emission from these objects is an extension of the radio spectrum. Crab-like sources have a high probability of containing a compact (unresolved) source of x-ray emission which in analogy to the Crab Nebula, is identified as the central stellar remnant.

The general absence of either compact x-ray sources or Crab-like diffuse nebulae within shell sources indicates that active pulsars are not usually formed in SN events which eventually form shell sources. However, there are several examples of remnants which share both shell and Crab-like characteristics so we cannot rule out an evolutionary connection between these two classes of SNR.

Introduction

The radio and optical morphology of the Crab Nebula are strikingly distinct from those of most galactic supernova remnants (SNR). The distinguishing radio characteristics include a flat spectrum, a filled-center brightness distribution, and a centrally-located pulsar. (Weiler and Shaver 1978). In contrast, shell-type remnants exhibit relatively

J. Danziger and P. Gorenstein (eds.), Supernova Remnants and their X-Ray Emission, 321–328.

https://doi.org/10.1017/S0074180900034057 Published online by Cambridge University Press

steep spectrum and a shell structure. The radio emission from both the Crab Nebula and shell remnants is linearly polarized indicating a synchrotron emission mechanism. Since the recognition that 3C58 shared many of the radio characteristics of the Crab Nebula (Weiler and Seielstad 1971), a growing number of galactic radio sources have been suggested as Crab-like SNR or plerions (for a review, see Weiler and Panagia 1980).

The study of Crab-like remnants as x-ray sources has developed much more slowly. Prior to the launch of the Einstein Observatory, only two Crab-like SNR had been detected, the Crab Nebula and Vela X. We might note that these were the only two remnants known to contain radio pulsars prior to Einstein. In fact, up till then, only one other SNR, W50, was known to contain a stellar remnant of any kind. The improved sensitivity of the Einstein Observatory over that of previous x-ray satellites (Giacconi et al 1979) has allowed us to study many more SNR, both shell-type and Crab-like, than previously possible. (for summary, see Table I). In this paper, I hope to review the current status of x-ray observations of Crab-like SNR.

TABLE I. - COMPACT OBJECTS IN CRAB-LIKE SNR

Name	%of X-ray Emission	Pulsed
Crab	∿ 5	Yes
3C58	∿ 5	No
Vela X	∿ 33	No
MSH 15-52	∿ 20	Yes
CTB 80	∿ 25	No
G21.5-0.9	< 5	---
G29.7-0.3	< 15	---

Stereotypical Crab-like SNR

As discussed by Weiler and Panagia (1980) while some SNR share all the morphological traits of the diffuse radio emission from the Crab Nebula, others appear to be a conglomeration of both Crab-like and shell attributes. There are only 5 unambiguous, Crab-like objects discovered to date. They are the Crab Nebula, Vela X, 3C58, (Weiler and Seielstad 1971) G21.5-0.9, (Becker and Kundu, 1976) and G74.9+1.2 (Duin et al 1975). All five have been studied with the Einstein Observatory. The first three are the best studied, having been observed with the IPC, the HRI, and the SSS, (see Becker, Helfand and Szymkowiak 1982 and references therein). All three exhibit a filled-center x-ray brightness distribution, all three contain unresolved x-ray sources (presumably stellar remnants) and all have non-thermal x-ray spectra. Only the stellar remnant in the Crab Nebula is observed to pulse.

The detection and study of the stellar remnant is hindered by the filled center morphology of the diffuse emission. The emission from the Crab pulsar is separable from the nebula by the very fact that it pulses. For 3C58 and Vela X, the separation of compact and diffuse component is more difficult, requiring a modeling of the diffuse surface

https://doi.org/10.1017/S0074180900034057 Published online by Cambridge University Press

brightness.

IPC and HRI observations of G21.5-0.9 reveal a filled-center brightness distribution coincident with the radio source but no point source was detected (Becker and Szymkowiak 1981). IPC observations of G74.9+1.2 reveal diffuse emission consistent with a filled-center distribution (Wilson 1980). The IPC, lacking sufficient resolution, would not have been able to distinguish a point source within G74.9+1.2.

The x-ray data from the five detected remnants listed above were discussed in detail by Becker et al (1982). They postulated that the ratio of x-ray to radio luminosity (L_X to L_R) could be used as an indication of the age of the remnant, noting that as the break in the synchrotran spectrum moved down in frequency, the ratio of L_X to L_R should decrease. This led to the conclusion that 3C58 was much older than the previously conjectured association with SN1181 would imply.

Ambiguous Crab-like Remnants

In recent years, the distinction between Crab-like and shell remnants has become blurred as some SNR have been found to share properties of both groups. Typically, these SNR are composed of a Crab-like radio component found inside a steep spectrum radio shell. Examples of this morphology are CTB80, G326.3-1.8, W28, and G29.7-0.3. All four of these SNR have been imaged by the Einstein Observatory.

The remnant CTB80 has a flat specrrum radio core with extensions to the north, east, and west in which the spectra become progressively steeper away from the core (Angerhofer et al 1981). The HRI image of CTB80 reveals as unresolved x-ray source coincident with the radio core surrounded by diffuse x-ray emission. (Becker et al 1982). The low ratio of L_X to L_R suggested that this object is substantially older than the Crab Nebula.

High resolution radio images of G29.7-0.3 have revealed that the source is composed of several steep spectrum components arranged in a shell, of about 2 arcmin diameter. An additional radio component within the source appear to have a flatter spectrum (Becker and Kundu 1976). The IPC and HRI images revealed x-ray emission emanating only from the flat Crab-like component (Becker, in preparation). The x-ray spectrum was highly absorbed resulting in too low a count rate for the HRI to detect the presence of a point source within the diffuse emission. The ratio of L_X to L_R exceeds that of any other Crab-like SNR, suggesting that G29.7-0.3 is a very recently formed remnant.

Two other remnants are known to be composed of steep spectrum radio shells which contain nonthermal, flat spectrum components, G326.3-1.8 (Milne et al (1979) and W28 (Andrews et al 1982). Both objects have been observed with the IPC and HRI. Although G326.3-1.8 shows diffuse x-ray emission associated with its shell, there is no enhancement in the vicinity of the Crab-like core (Becker, in preparation). The same is true for W28 (Long 1979). However W28 does

https://doi.org/10.1017/S0074180900034057 Published online by Cambridge University Press

contain an unresolved x-ray source several arcmin outside of the Crab-like core but within the larger shell. (Andrews et al 1982).

Usually, remnants are catagorized by their radio attributes, primarily because remnants typically are studied best at radio wavelengths Therefore it is unusual to classify a remnant as Crab-like when it does not share the radio morphology of the Crab Nebula. If we expand our definition of Crab-like to include all SNR in which a compact stellar remnant appears to be injecting energy into the diffuse nebula, then we must include W50 and MSH 15-52 (G320.4-1.2) in the discussion.

The optical studies of SS433 which is situated within W50, certainly indicate that W50 meets this criteria. X-ray observations of SS433 with the IPC and HRI show it to be an unresolved x-ray source surrounded by a diffuse source of x-ray emission which is elongated in the east-west direction (Seward et al 1980). At present there is no evidence that W50 contains a flat spectrum radio component.

Similarly, radio maps of MSH 15-52 reveal a steep spectrum shell typical of shell remnants (Caswell, Milne, and Wellington 1981). However, Seward and Harnden (1982) have reported the presence of a compact x-ray source within the remnant which has a 0.150 s pulse period and is surrounded by diffuse x-ray emission. The x-ray data alone are convincing that we are observing a Crab-like object and one suspects that more sensitive radio observations will reveal a radio counterpart.

Discussion

Although we generally use several specific radio characteristics to define the class of Crab-like SNR, these characteristics are really diagnostics used to infer the presence of a stellar remnant which is continually injecting energy into the remnant. To that extent, it is the existence of this stellar remnant which is the defining characteristic of a Crab-like or "pulsar-driven" remnant. Therefore, the observation of a compact object within such an object speaks most directly to its intrinsic nature. The discovery of compact x-ray sources in four additional Crab-like SNR (3C58, CTB80, W28 and MSH 15-52) is probably the Einstein Observatory's most important contribution in this area (see Table I for summary of compact source data).

In analogy to Crab Nebula, we assume that the diffuse emission at all wavelengths is the result of synchrotron emission from relativistic electrons accelerated by the central stellar remnant. The highest energy photons derive from the highest energy electrons which in turn have to shortest lifetimes. Therefore, the x-ray emission is related to the most recent pulsar energy losses, while the radio emission is an integrated measure to the pulsar's total energy loss. In effect, the x-ray emission should track the pulsar energetics more closely than longer wavelength emission. However, this conclusion relies heavily on the assumption that the x-ray emission is non-thermal synchrotron emission.

This has been shown conclusively for the Crab Nebula for which the x-ray emission is known to be polarized and to obey a power-law spectrum. Spectral data are also available for 3C58 (Becker et al 1982), Vela X (Pravdo et al 1976) and MSH15-52 (Szymkowiak, private comm.), all of which have nonthermal power-law spectra. X-ray spectral data do not exist for the remaining Crab-like SNR and this is the area most in need of additional observations. Until the x-ray emission from these other remnants is demonstrated to be non-thermal, the interpretation of the x-ray emission will remain uncertain.

If we accept the synchrotron nature of the x-ray emission, then it follows that the x-ray emission will be the best indication of the evolutionary state of a Crab-like remnant. Since the x-ray emitting electrons are short-lived, the x-ray luminosity should decrease as the energy injection rate decreases. In addition, as the relativistic electron population evolves, the break in the emission spectrum will move towards lower frequency, resulting in a decrease in the ratio of L_X to L_R giving a distance independent measure of the age.

The time dependence of the x-ray luminosity of a Crab-like SNR will be proportional to that of the pulsar itself if the efficiency for production of relativistic electrons remains constant. One functional form for the time dependence of a pulsar, as suggested by Goldreich and Julian (1969) and Pacini and Salvati (1973) is

$$L= L_o/(1+t/T)^{(n+1)/N-1)}$$

where $2L_o$ is the initial rate of energy loss, T is the characteristic spin down time, and n the braking index. For t>>T the equation reduces to

$$L = 2L_o(T/t)^{(n+1)/(n-1)}.$$

Wilson used this relationship to compare the age of G74.9+1.2 to the Crab Nebula with the implicit assumption that L_o, T, and n are the same for both. If so, then the ratio of luminosities for the two SNR implies an age of 6-9 x 10^3 years for G74.9+1.2. This procedure suffers from the uncertainty in the remnant's initial conditions. Furthermore, the age calculated for G74.9+1.2 is inversely proportional to its assumed distance, a poorly determined quantity.

In an attempt to eliminate the dependence of age on distance, Becker et al (1982) attempted to formulate an age dependent parameter based on the evolution of the energy spectrum of relativistic electrons in a magnetic field. For two extreme cases, continuous injection of electrons vs instantaneous injection of electrons, they found $L_X/L_R \propto B^{-1.5}\, t^{-1}$ or $B^{-3}\, t^{-2}$ respectively, where B is the magnetic field strength and t the remnant age. The ratio L_X/L_R would be a valid age indicator if we assume the B is the same within all Crab-like remnants. However, high magnetic

https://doi.org/10.1017/S0074180900034057 Published online by Cambridge University Press

fields would have the effect of "ageing" a remnant prematurely. For the Crab and Vela X, with ages of ∿ 900 years and ∿ 12,000 years respectively, the ratio of L_X/L_R is 140 and 0.1 respectively. This ratio suggests that either the injection of electrons approximate an instantaneous injection or that the fields in Vela X is higher than in the Crab Nebula. Values of L_X/L_R for the other Crab-like SNR are given in Table II. In the newly found x-ray object within MSH 15-52, no diffuse radio counterpart is observed (Caswell et al 1981), suggesting L_X/L_R is high, consistent with the young age implied by the spin down rate (Seward and Harnden 1982).

TABLE II. RADIO AND X-RAY LUMINOSITIES OF CRAB-LIKE SNR

NAME	DIST. (kpc)	DIAM. (pc)	L_R (ergs/s)	L_X (ergs/s)	RATIO
G29.7-0.3	19	3	5×10^{33}	3.5×10^{36}	500
Crab	2	3.5	1.8×10^{35}	2.5×10^{37}	100
G21.5-0.9	4.8	2.3	1.7×10^{34}	2.6×10^{35}	15
MSH 15-42	4.2	∿2.0	2×10^{34}	2.6×10^{35}	10
CTB 80	3	∿5	5.2×10^{32}	8×10^{32}	1.6
G74.9+1.2	12	27	6.1×10^{34}	8×10^{34}	1.3
3C58	8	8	1.7×10^{35}	1×10^{35}	.6
Vela X	.5	24	2.4×10^{34}	3×10^{33}	.1

The diffuse x-ray emission in a Crab-like remnant should serve as a guidepost to the location of the stellar remnant even when a stellar remnant is not observed. Since radio emitting electrons are long-lived, the centroid of the radio emission can be displaced from the pulsar location if the pulsar has significant space velocity, as is the case with Vela X. But short-lived x-ray emitting electrons do not have time to move away from the pulsar, so we expect the pulsar to be coincident with the diffuse x-ray centroid. Thus even when the pulsar is undetected, its location can be localized.

A related issue to the two contrasting types of SNR, ie Crab-like and shell, is the question of the origin of pulsars. Statistical studies of pulsars typically lead to the conclusion that the galactic pulsar birth rate is one every 10-25 years (for instance Vivehanand and Narayan 1981). With the near completion of surveys of SNR in radio and x-rays for Crab-like objects, we can examine results in a more quantitative way. What we have seen is that Crab-like SNR can be isolated objects or part of a shell remnant. Observationally, there is no discernible difference between Crab-like sources inside or outside of shells and similarly, the evolution of the shell may be unaffected by the presence of a Crab-like core. Therefore, these two aspects of SNR are decoupled, each following independent evolutionary tracks.

I'd also like to assert the likelihood that a large fraction of SN produce pulsars, at least to a 1st approximation. This is based on the pulsar space density, and the expected SN rate in our galaxy. Unless pulsars are formed in other ways, most SN must result in pulsars. But of the ∿ 100 shell remnants, only 4 contain pulsar-driven remnants, i.e., one in twenty-five. What of the other 96%? As has been suggested by others, perhaps most neutron stars are not formed as active pulsars, but only turn on much later at slower periods, long after the shell has dispersed and too weak to form observable Crab-like remnants. If so, then the data tells us the percentage of early pulsar turn-on, namely 4%.

But what if the pulsar-driven remnant development is truly independent of the shell development. Then for every shell-less Crab-like object there should be 24 shell-less remnants in which the pulsar does not turn on. Since the number of shell-less Crab sources equals the number inside of shells, then the number of shell-less pulsar-less remnants should equal the number of empty shell remnants. How does a shell-less, pulsar-less SNR appear? It doesn't, therefore 50% of all SN do not produce observable remnants.

In conclusion, I would stress the need for additional observations. Spectra are available for only three Crab-like SNR. Furthermore, in many cases where images are available, they are of very poor statistical quality. Hopefully these objects will be given high priority in any future x-ray mission.

Acknowledgements

This work was supported in part by Nasa Grant NSG 8-432. I want to thank Helen Hatcher for preparing the manuscript for publication.

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DISCUSSION:

HELFAND: To comment on Dr. Weiler's point, we have searched 30 of the 60 shell-like SNR within 5 Kpc with the Einstein Observatory. We could have observed a Vela-like source in any of these and we have not seen them. Thus, this limit mentioned by Dr. Becker is a meaningful one.

BECKER: Thank you, David. I'd also point out that Crab-like components are clearly absent from the very young SNR such as Cas A, Tycho, Kepler, and SN1006. We can conclude that these objects do not contain active pulsars.

TUOHY: I would like to point out that there is another Crab-like SNR which has not yet been mentioned, namely N157B in the Large Magellanic Cloud. This remnant has a filled centre radio structure and a flat radio spectral index. Also, the recent solid state spectrometer observations by Clark et al (1982) show that the x-ray spectrum appears smooth, as expected for synchrotron emission.

BECKER: Yes, I agree that N157B should be included. A calculation of the ratio of L_X to L_R gives a value of ~ 5. Neither at the high or low ends of the range of observed ratios.

MCKEE: Since most of the Crab-like remnants you have discussed are young, whereas most of the known shell-like SNR's in the Galaxy are old, it appears to me that the Crab-like phase is short-lived and that the fraction of SNR's with pulsars significantly exceeds the fraction which are Crab-like. Would you comment?

BECKER: The Crab-like nebula surrounding the Vela pulsar is probably 10,000 years old, so since most observed SNR are no older than this, the Crab-like components would still be present.