NEUTRON STARS IN TWELVE SUPERNOVA REMNANTS

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ABSTRACT. X-ray observations of selected SNR are summarized. Five contain internal spinning neutron stars--four isolated and one in a binary system. Another seven contain central unresolved sources or bright nebulae. Observations of these nebulae, probably due to synchrotron emission, are used to estimate characteristics of the unseen pulsars.

1. Introduction

Neutron stars are believed to originate in the gravitational collapse of cores of massive stars, which is calculated to be very rapid, and deep within the interior of red giant stars. When the resulting shock reaches the outer layers, the visible light of a supernova is produced, and at much later times we observe energy from the interaction of the expanding stellar debris with surrounding material. The shells of supernova remnants are visible for thousands of years and most can be observed at radio, optical and X-ray wavelengths. The shells of remnants which contain pulsars (= neutron stars) can reveal something about the precursor star, perhaps the mass and composition of the outer layers at the time of collapse.

If the neutron star is isolated its period (P) and period derivative ($\dot{P}$) can be used to calculate its characteristic age (A), and the rate of rotational energy loss ($\dot{E}$). Rotational energy is transformed to a relativistic wind of charged particles and magnetic field. High energy electrons radiate synchrotron radiation in the magnetic field and young pulsars observed within supernova remnants are apparently always surrounded by diffuse synchrotron emission. Observations have been summarized in recent reviews listed by Seward (1985).

D. J. Helfand and J.-H. Huang (eds.), The Origin and Evolution of Neutron Stars, 99–108.

2. The Crab Nebula

The supernova of 1054 and the Crab Pulsar remain the only indisputable example of a supernova associated with the formation of a neutron star. The location of the remnant is the same as that of the SN, the characteristic age ($P/2\dot{P}$) of the pulsar is only 30% higher than the age of the remnant, and the calculated pulsar rotational energy loss is exactly that needed to power the bright nebular radiation observed at all wavelengths.

In the X-ray band the Crab is the brightest SNR in our galaxy. All-sky X-ray surveys have found no other SNR as luminous in the Milky Way. 96% of the soft X-ray luminosity comes from the synchrotron nebula, which has the highest surface brightness of any diffuse X-ray source observed by Einstein (Harnden & Seward, 1984). It is this bright synchrotron nebula that gives the Crab its distinct character. Why is this so strong?

Among SNR, the Crab has two anomalous features: the rapid pulsar, which deposits energy in the interior, and the low expansion velocity of the optical filaments. These filaments, formerly the outer layer of the star, confine the pulsar-deposited energy to a relatively small volume and the consequent high energy-density gives the Crab its unique properties. Optical and X-ray continuum radiation is confined to the volume bounded by the filaments. Radio emission is brightest close to bright filaments, indicating a compression of the nebular magnetic field flowing from the vicinity of the pulsar. The spectral measurements of Henry & McAlpine (1982) indicate that the filaments contain more than one solar mass of hydrogen and helium, and confirm the finding of others that helium is overabundant. Henry and McAlpine calculate that 60% of the mass is helium. This is the only evidence for a substantial enrichment over solar abundance in the debris from SN1054.

The X-ray synchrotron nebula occupies a small volume at the center. The brightest emission comes not from an area surrounding the pulsar, but is centered approximately 10" northwest of the pulsar, indicating the existence of processes which accelerate electrons within the nebula, rather than a simple flow of high-energy electrons from the pulsar which lose energy as they diffuse outward. The small size of the X-ray nebula shows the lifetime of the relativistic electrons producing X-rays is shorter than the time it takes these electrons to diffuse to the edge of the Crab.

After the discovery of the Crab pulsar in 1968, the early evolution of pulsars was thought to be understood: Pulsars form spinning rapidly and lose energy at a high rate. We have found, however, no other object in our galaxy with a synchrotron nebula as bright as that of the Crab. Pulsars and surrounding nebulae in other remnants are all less luminous than in the Crab. The neutron star within the Crab Nebula is the brightest object in its class rather than a typical young pulsar.

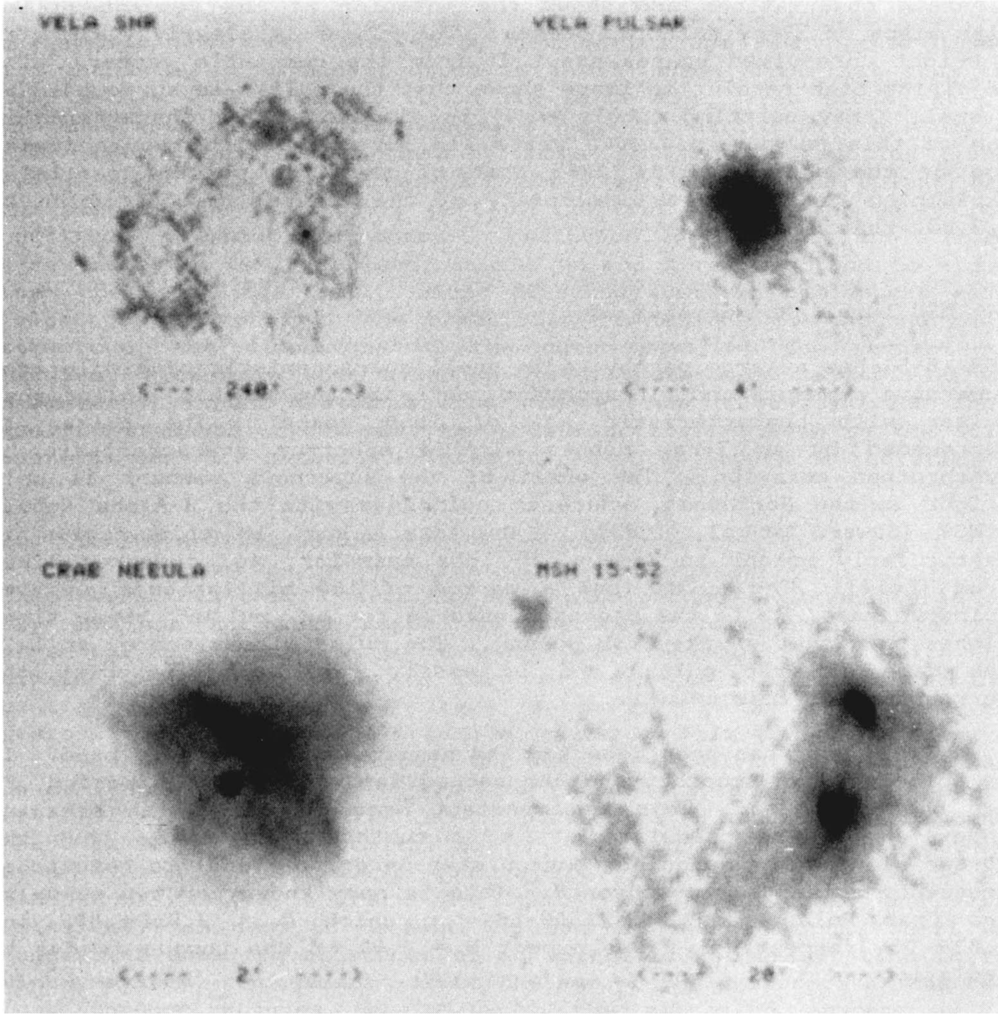

Fig. 1: Einstein pictures of SNR with internal isolated neutron stars.

3. The Vela Supernova Remnant

Soon after the pulsar in the Crab Nebula was discovered, a second was found within the Vela SNR. At a distance of 400 pc, the Vela remnant is over 5° in diameter, and intrinsically older and larger than the Crab. The Vela pulsar is the closest young, active pulsar to Earth and offers unique observing opportunities. Not only can low-luminosity features be detected, but the small column density of interstellar material allows transmission of soft X-rays that are unobservable from other remnants. Thus intense soft X-ray emission is detected from the shell of the Vela SNR and low surface brightness emission can be seen surrounding the pulsar itself (Harnden et al,

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1985). The composite image in Figure 1 was made from 40 separate Einstein observations and shows the interior of the remnant filled with wisps of X-ray emitting plasma. The pulsar is clearly visible as a bright unresolved source about 1° from the remnant's center. The adjoining high-resolution image shows that the pulsar is surrounded by a small X-ray emitting nebula ~ 4' in diameter. The characteristic age of this pulsar is 11,000 years, in agreement with the estimated age of the shell. $\dot{E}$ is 1/65 that of the Crab pulsar, partially explaining the low X-ray luminosity of the central nebula, which is 1/5,000 that of the Crab.

4. MSH 15-52 and PSR 1509-58

MSH 15-52 has a large patchy radio shell characteristic of middle-aged supernova remnants and, in apparent contradiction to this, an internal pulsar with characteristic age of 1550 years. The pulsar is surrounded by an X-ray nebula with a spectrum characteristic of synchrotron emission. The shell of the supernova remnant is only bright in the Northwest, where it coincides with the H-Alpha Nebula RCW89 (Seward et al, 1983). One small knot in this region is particularly bright in X-rays, H-Alpha emission, and infrared lines from [FeII]. The pulsar has a period of 150 milliseconds and its spindown rate, $\dot{P}$, is the highest measured for any pulsar, three times higher than that of the Crab pulsar. The pulsar loses energy at 1/25 the rate of Crab pulsar and is easily capable of powering the surrounding diffuse nebula.

The pulsar has been detected and monitored in the radio band. It is spinning down smoothly and the second derivative of the period, $\ddot{P}$, has been measured. This is important because with $\ddot{P}$ the breaking index, N, can be calculated. It is customary to assume that the torque slowing the spinning neutron star is proportional to rotational frequency raised to the power N. This is only known for two pulsars, the Crab Pulsar and PSR 1509-58 for which $N = 2.515 \pm .005$ and $2.83 \pm .03$, respectively. We expect $N = 3.00$ if the torque is due to radiation reaction alone.

The surrounding nebula is much larger than that surrounding the Crab pulsar and not as luminous. The X-ray surface brightness is only 2×10^{-5} that of the synchrotron emission of the Crab and the total X-ray luminosity is 1/100 that of the Crab Nebula. The surface brightness of the nebula around PSR 1509-58 is too small to detect in radio or optical bands. The nebular magnetic field calculated from the X-ray data is about 10^{-5} Gauss, a factor of 20 below that within the Crab, which characterizes the great difference in X-ray surface brightness within the two remnants.

5. SNR 0540-69.3

This remnant is in the Large Magellanic Cloud and is closer in character to the Crab than any other remnant so far observed.

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The pulsar has a period of 50 ms and a spindown rate 13% higher than that of the Crab pulsar, so $\dot{E}$ is 1/3 that of the Crab pulsar. Optical pulsations have been observed by Middleditch and Pennypacker (1985) and the X-ray continuum spectrum is a bit harder than that from the Crab Nebula. The remnant is in the Large Magellanic Cloud, so its distance and luminosity are known, a happy situation in the study of SNR. Deep optical photographs by Chanan, Helfand, & Reynolds (1985) reveal an 8" diameter oxygen-rich shell surrounding the pulsar (2/3 the size of the filamentary part of the Crab Nebula) and an optical continuum, presumably synchrotron radiation, within this shell. The X-ray emission is 23% pulsed, so the pulsed X-ray fraction is higher than the 4% of the Crab. Since existing southern hemisphere radio telescopes do not have the capability of detecting arcsecond radio structure, the dimensions of the outer part of the remnant are unknown. There is some evidence for a radio outer shell ~ 2" in diameter. Unlike the Crab, the remnant has an oxygen-rich inner shell. It seems likely that the precursor star evolved to the point where oxygen rich material existed in the outer layers of the star.

6. CTB 109 and 1E2259+586

This remnant is only 3° from Cas A, the brightest radio source in the sky and was not well mapped in the radio band until after its serendipitous discovery by Gregory and Fahlman (1980) with the Einstein IPC. On the eastern side, an X-ray shell surrounds a bright central unresolved source. There is no radio or X-ray shell on the western side because of a molecular cloud in this region (Gregory et al, 1983). In this dense cloud the shock has evolved more rapidly and is no longer radiating. X-rays from the central source have a period of 6.985 s, confirming the identification as a neutron star. Since there is evidence for orbital motion, the pulsar is probably powered by accretion. The optical counterpart is very faint (B=23.5) and cannot be massive. There are inner regions of radio and X-ray emission which seem to connect the central source to the shell and suggest to some the existence of an energetic jet originating in the binary system. Information about the age of the neutron star has been lost through torques generated by the accretion process. The precursor star cannot have been very massive or this close binary system would have been disrupted by the explosion. Mass ejected by the SN explosion is estimated as only a few tenths of a solar mass.

Table 1. Pulsars in SNR

Pulsar Name	P (s)	$\dot{P}$ (10^{-15}s/s)	$\dot{E}$ (10^{38} erg/s)	Age (10^{3} yr)	Remnant Name
Crab	0.033	423	4.7	1.24	Crab
0540-69	0.050	479	1.5	1.67	0540-64.3
1509-58	0.150	1540	0.18	1.55	MSH 15-52
Vela	0.089	125	0.071	11.3	Vela xyz
1E2259+586	6.98		-in binary system-		CTB 109

7. The Four Young Isolated Pulsars

Thus, we know of four isolated pulsars within SNR, and the regular pulsations give positive identification as rotating neutron stars.

The waveform of the pulses emitted differs greatly among the individual objects. The Crab Pulsar shows two sharp pulses separated by 140° of phase from radio frequencies to γ-ray energies. The pulsar in the LMC has an X-ray and optical waveform which is almost sinusoidal but with structure at the maximum. No radio pulsations have been observed, but the pulsar is so distant that it would have to be abnormally strong to be above the detection threshold. The pulsar within MSH 15-52 also has a sinusoidal waveform in X-rays. It has been detected in the radio band, but not optically. The radio duty cycle is $\sim$ 10% and the X-ray duty cycle $\sim$ 50%. The pulse shape for the Vela pulsar varies with frequency. It progresses from a single sharp radio pulse to a crab-pulsar-like double pulse at γ-ray energies where most of the pulsed energy is emitted. No pulsations have been detected in X-rays down to a level of $\sim$ 1%.

These variations might be due, at least partially, to variations in geometry. The pulse shape we see is dependent on the orientation of the line of sight, the spin axis, and the magnetic axis of the pulsar. The mechanism by which pulsars emit radiation is not well understood.

8. Unresolved Sources within Supernova Remnants

Four remnants contain unresolved sources likely to be neutron stars. High resolution Einstein observations show the sources clearly but do not contain enough counts to make a decent search for pulsations possible. So, no pulsations, X-ray or radio, have been detected from these faint objects.

3C58, a radio source full of faint optical filaments and at a distance of 2.6 kpc, is probably the most interesting. The linear size of the remnant is 50% larger than the Crab Nebula, but it is 1700 times less luminous. The interior of the remnant shows diffuse X-ray emission with a faint unresolved source at the center (Becker et al, 1982). This is commonly accepted as the remnant of SN 1181. It is thus a young remnant with an interior neutron star 2,000 times less luminous than the one within the Crab Nebula, implying a much lower rate of energy loss. Here is the importance of historical identification. If correct, we know that neutron stars can be born with low luminosity and that all young neutron stars are not easy to detect.

CTB80 is, in some ways, similar to 3C58, and has been suggested by some to be the remnant of SN 1408. In X-rays it appears as a faint diffuse source of extent $\sim$ 5' surrounding a weak unresolved object, probably a neutron star (Wang & Seward, 1984). The area around the neutron star contains faint optical filaments and is a fairly strong radio source. The radio appearance of this remnant, however, is unique. Three faint radio arms extend a distance of ~ 30' and no shell-like structure is observed. If the remnant is young, these arms require material to move at ~ 0.15 c. Another possibility is the superposition of a young SNR and an older one.

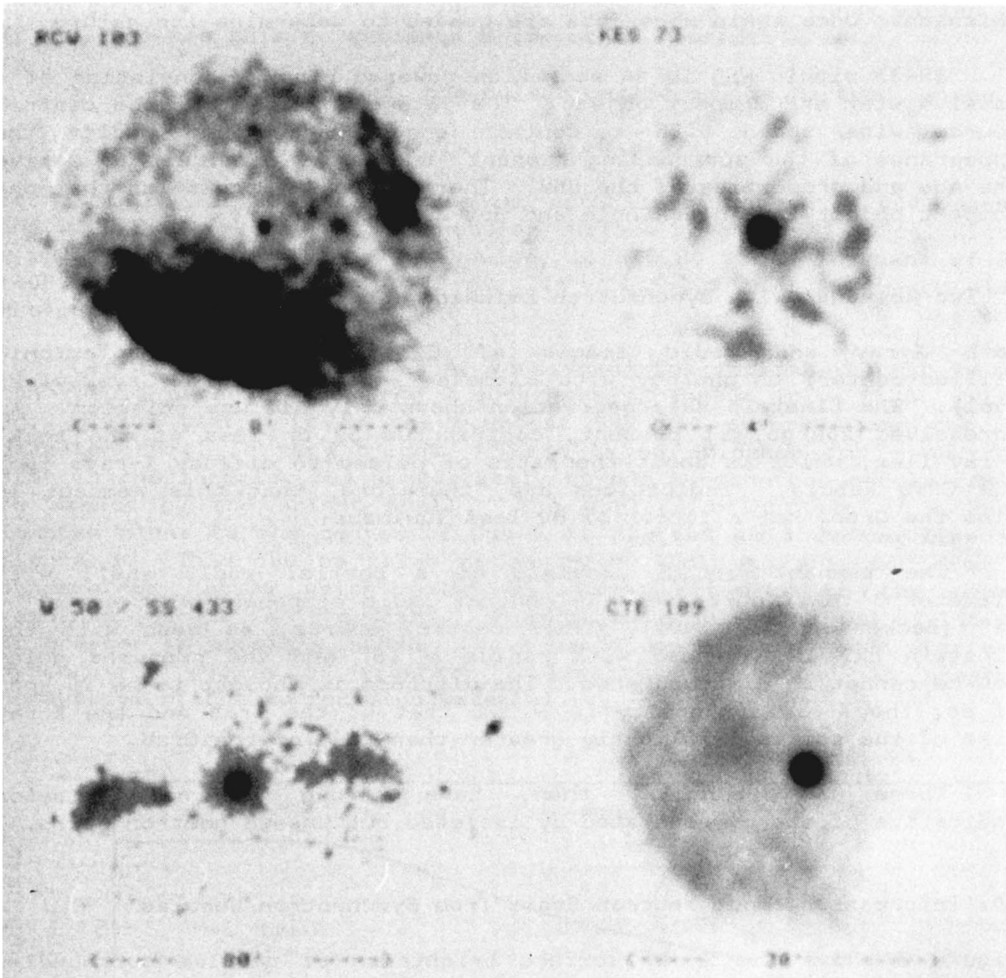

Fig. 2: Einstein pictures of SNR with internal unresolved sources.

RCW 103 is more conventional. It has an X-ray and radio shell of diameter 8', the same as the diameter of Tycho's SNR. At precisely the center, there is an unresolved X-ray source just above detection threshold. No diffuse emission obviously connected with this compact source is seen, but this could easily be obscured by thermal emission from the shell. Touhy, et al (1983) have searched for an optical counterpart and found nothing brighter than V=22 mag. They conclude this is an isolated neutron star and the X-rays are thermal emission from the hot surface. A longer X-ray observation is needed to collect enough counts to do a definitive search for pulsations.

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At the other extreme, the internal source within Kes 73 is moderately bright, but the surrounding diffuse emission is ill-defined. Kriss et al (1985) consider it most likely that this source is an accretion powered binary, a reasonable hypothesis since its luminosity is high compared to the surrounding synchrotron emission. Once again more data are needed to determine its nature.

SS433 within W50 is an accretion powered binary, consisting of a massive star and compact object. The jets emanating from the central source with speed 0.26 c contain enough energy to modify the appearance of the surrounding remnant, and it is difficult to derive the age and properties of the SNR. There is some speculation that the compact object is a black hole and not a neutron star.

9. Two Remnants with Synchrotron Emission (and unseen pulsars?)

Both X-ray and radio images of G21.5-0.9 show a plerionic (filled-center) morphology with diameter ~ 1' (Becker & Szymkowiak, 1981). The Einstein HRI observation shows only diffuse emission. An unresolved source, if present, contributes 5% or less of the total X-ray flux, which is about the ratio of pulsed to diffuse X-rays from the Crab Nebula. Indications are, therefore, that this remnant is like the Crab, but a factor of 80 less luminous.

The remnant Kes 75 consists of a partial radio shell with diameter 3' half surrounding a central radio component with extent ~ 30" (Becker et al, 1982). This central source, as seen with the Einstein HRI is extended with radius ~ 15" and the presumed point source cannot be distinguished. The distance is thought to be 20 kpc. If so, the X-ray luminosity is ~ 1/5 that of the Crab and the X-ray size of the source is slightly greater than that of the Crab.

These two remnants, then, have strong internal emission indicative of energy generated by isolated but unseen neutron stars.

10. Information about Neutron Stars from Synchrotron Nebulae

Figure 3 shows the X-ray surface brightness of nebulae surrounding pulsars or unresolved sources in these SNR. These curves were obtained by subtracting the point response function of the Einstein telescope from the average surface brightness measured radially from the unresolved source. The distances listed by Seward (1985) have been used to set the linear scale. If the distance is not correct the radial scale will shift but the value of the surface brightness will remain constant. The calculated surface brightness does, however, depend critically on assumed X-ray absorption in the ISM.

The pulsar in the Large Magellanic Cloud is too distant for us to separate any surrounding synchrotron nebula from the pulsar. We know that 77% of the emission from this region is not pulsed and we can speculate on the strength of the nebula around the pulsar, but we have no measure of its dimensions.

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Figure 3 implies that Kes 75 and G21.5-0.9 contain pulsars with high rates of energy loss. Most other remnants cluster about MSH 15-52. These data can be used to estimate properties of the neutron stars. We arbitrarily use the measured surface brightness 0.3 pc from the central source to characterize the emission. Using the three known pulsars as calibration, we find the surface brightness varies as $(\dot{E})^{2.5}$, and use this to estimate $\dot{E}$ for other remnants.

If $\dot{E}$ and age are known, the pulsar period may be derived, since

$$P(s) = .055\ A^{-1/2}\ (\mathrm{Kyrs})\ \dot{E}^{-1/2}\ (10^{37}\ \mathrm{erg/s}).$$

For example: if 3C58 is the remnant of SN1181, its age is 800 years; and with $\dot{E}$ estimated from the nebular surface brightness, we calculate a pulsar period of 210 ms. Likewise, if CTB 80 is the remnant of SN 1408, the pulsar period is 280 ms. If G21.5-0.9 is 1,000 years old, the pulsar period is 125 ms.

Let us also consider Cas A, an oxygen rich remnant thought to be the result of an unseen Type 2 supernova explosion in ~ 1670. With age of 300 years, it is the youngest SNR yet observed and the 3' diameter shell is very bright. There is no evidence for a neutron star in the interior but a moderately strong synchrotron nebula could be masked by the bright shell. The surface brightness of a knot located close to the center of Cas A is plotted as a dashed line in Figure 3. This can be taken as an upper limit to emission from a synchrotron nebula which could be bright compared to the other remnants (except for the Crab). We estimate a pulsar period of 145 ms or greater is possible. Thus, Cas A could contain a neutron star and synchrotron nebula of moderate luminosity, undetected at present because of bright surrounding material.

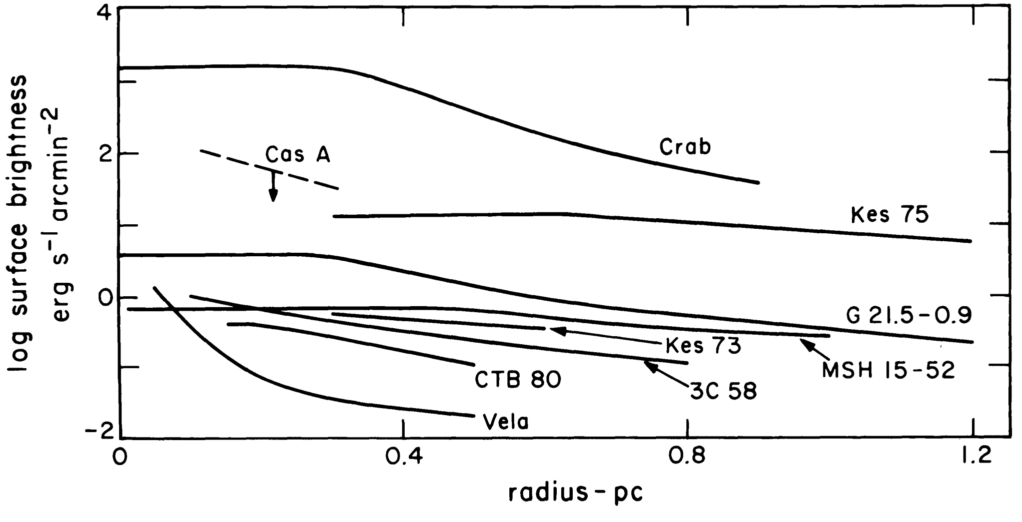

Fig. 3: Surface brightness of X-ray synchrotron nebulae.

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11. Conclusions

The Einstein observations were more sensitive than radio and optical techniques in the detection of low-surface-brightness nebulae, and in some cases, the pulsed radiation from young pulsars.

We have reviewed twelve remnants. Four contain isolated neutron stars, two contain compact objects in binary systems, and six show evidence for compact objects or energy deposited by them in the central region. The surrounding remnants are all different. Some have shells some do not. Some have oxygen rich material some do not. Some perhaps have jets emanating from the central object.

Perhaps these differences in the appearance of SNR shells reflect differing conditions during gravitational collapse and formation of the neutron star; and neutron stars can be formed from a great variety of progenitor stars. Although variations due to age and the surrounding interstellar medium are important, the young remnants should reflect the characteristics of the progenitor stars.

It seems clear that some young neutron stars have low luminosity. So far we have only detected the brightest. It is likely that some are born in an "inactive" state, and have never been strong X-ray emitters. They might be formed with long rotation periods or they may spin rapidly but have weak initial magnetic fields. Present observations indicate that there is no shortage of neutron stars within SNR. Instruments of greater sensitivity should lead to more identifications and to a fuller understanding of neutron star formation.

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