X-RAYS FROM RADIO PULSARS: THE PORTABLE SUPERNOVA REMNANTS

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ABSTRACT

Neutron stars are the longest-lived remnants of supernova explosions. As a reservoir of thermal energy remaining from the explosion and generated by frictional coupling between core and crust, as a storehouse of magnetic and rotational kinetic energy which allows the star to act as a high energy particle accelerator, and as the source of a deep gravitational potential which can generate heat from infalling matter, neutron stars remain capable of producing high energy radiation for a Hubble time. We review here the results of an extensive survey of supernova remnants and radio pulsars with the imaging instruments on board the Einstein Observatory and discuss the implications of these results for pulsar physics and for the origin and evolution of galactic neutron stars.

I. INTRODUCTION

The concept of a neutron star was first discussed over fifty years ago. Confirmation that such stars exist is dated from the announcement in 1968 of the discovery of the first four pulsars by radio astronomers working at Cambridge University (Hewish et al. 1968). Over the past 15 years, the number of known radio pulsars has increased nearly a hundredfold, and a wealth of data on pulse intensities, polarization, spectra, and repetition rates has been accumulated. These data have been used to model the pulsar magnetosphere, probe the stellar interior, and study the origin and evolution of the galactic population of neutron stars. Yet the radio luminosities of most pulsars represent $\lesssim 10^{-5}$ of the stars' energy loss rate as measured from their increasing periods. The remaining rotational kinetic energy is converted to low frequency dipole radiation at the pulsar's spin frequency, higher frequency electromagnetic waves, and high energy particles in unknown proportions. We discuss herein a new diagnostic for the properties of isolated neutron stars: X-ray emission from radio pulsars.

X-ray astronomers had in fact been observing neutron stars as X-ray binaries for several years when the discovery of radio pulsars was announced, although it was not until the launch of the first X-ray satellite, Uhuru, that the description of these systems as a

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neutron star accreting matter from a normal companion became accepted. The first radio pulsar to be detected as an X-ray source was the youngest such object known - the pulsar at the center of the Crab Nebula (Fritz et al. 1969). Its X-rays are pulsed at the stellar rotation frequency and the pulse morphology is similar to that in the radio, optical, and gamma-ray spectral regimes; the X-ray to radio luminosity ratio $L_x/L_R \sim 10^6$. The only other radio pulsar detected as an X-ray source in the ensuing decade was the second-youngest pulsar known, PSR 0833-45 in the Vela supernova remnant (Harnden and Gorenstein 1973; Moore et al. 1974). Recent imaging observations have shown that the emission consists of an unpulsed X-ray point source centered on the pulsar surrounded by a ~2' diffuse X-ray nebula: $L_x/L_R \sim 3 \times 10^4$ (Harnden, this volume). Prior to 1980, the Crab and Vela were the only two radio pulsars detected outside the radio band, and they remain the only objects detected at optical and gamma-ray wavelengths.

The launch of the Einstein Observatory provided X-ray astronomers with a thousandfold increase in sensitivity to point sources emitting in the 0.1 to 4.0 keV band. With this new capability in mind, Helfand, Chanan, and Novick (1980) reviewed the prospects for detecting X-ray emission from isolated neutron stars and initiated a program of Einstein observations designed to further our understanding of radio pulsar interiors, magnetospheres, and evolution. In addition, a number of observers were surveying the X-ray emission from SNR within which young neutron stars might be found, and theorists, working on such problems as neutron star cooling, crust-core coupling, and magnetospheric emission mechanisms, were reassessing the levels of X-ray emission expected. The following is a preliminary review of the result of all the activity during the past three years.

2. X-RAYS FROM YOUNG PULSARS

2.1 Initial Cooling - Known Radio Pulsars

At the time of its creation in the supernova event, a neutron star is likely to have a temperature $T > 10^{10}$ K. It subsequently cools via both neutrino emission from the interior and photon emission from the stellar surface. The cooling rate is sensitive to a number of factors including the central density and composition (e.g., quarks, pions, or neutrons), interior superfluidity, magnetic field strength, and crustal properties. Thus, the temperature history of a young neutron star is a sensitive probe of stellar structure and, throughout the interval 10^{-3} yr $< t < 10^4$ yr, the temperature must be measured in the X-ray band.

Among the first theoretical work on neutron star cooling was that of Bahcall and Wolf (1965) who calculated expected surface temperatures for the purpose of assessing the likelihood that the newly discovered, luminous celestial X-ray sources were in fact hot neutron stars. They concluded that temperatures would remain in the range of 10^7-10^8 K for too short a time to explain the observed population of sources. The discovery of radio pulsars stimulated considerable further work in the following decade (see Tsuruta 1979 for a comprehensive review). These results may be summarized as a prediction that, barring exotic interior compositions, neutron star surface temperatures should remain above a few million degrees for a few thousand years after birth. The only observatinal datum was an upper limit to the nonpulsed radiation from the Crab pulsar obtained during lunar occultation (Wolff et al. 1975; Toor and Seward 1977); it led to an implied temperature of $T \lesssim 3 \times 10^6$ K.

Stimulated by the prospect of considerable observational progress offered by the imaging X-ray instruments on Einstein, (Giacconi et al. 1979) several groups have readdressed the problems of neutron star cooling over the past three years (Glen and Sutherland 1980; Richardson 1980; van Riper and Lamb 1981; van Riper, this volume; Nomoto and Tsuruta 1981 and this volume). These recent calculations have included full general relativistic thermodynamics, the effect of a finite thermal conduction timescale, a more realistic treatment of the structure of the thin envelope across which the temperature gradient is steepest, new equations of state, improved treatment of superfluid and magnetic field effects and the recalculation of accelerated cooling from quarks and pions. While the predictions disagree in some of their details, the general result has been lower expected surface temperatures. A star with standard composition is expected to have $T \lesssim 2.5 \times 10^6$ by $t \sim 100$ yr and to have cooled to $T < 1.5 \times 10^6$ at $t \sim 10^4$ yr. This represents a decrease in the expected X-ray luminosity for a young star of a factor $\gtrsim 50$ and it should be emphasized that enough remaining theoretical uncertainties have been identified that a further readjustment by a similar factor is not excluded.

The chief value of the Einstein observations with regard to the neutron star cooling question has been to stimulate the aforementioned theoretical work; no definitive examples of a cooling young neutron stars have been identified, although a few noteworthy observations have been achieved. Four known neutron stars have been observed to emit X-rays, although the contribution to this emission of surface thermal radiation remains unclear. From a survey of over 70 SNR in the Galaxy, a single candidate hot neutron star has been observed and a number of significant upper limits have been set. We review these results below.

For the case of the Crab pulsar, high resolution imager (HRI - 4" spatial resolution, ΔE = 0.1-3.5 keV) data show that the pulsar fades to ~1% of its peak value at phase ~0.85 from the main pulse (Harnden, this volume), a level similar to that seen in the nonthermal optical emission profile (Smith 1981). Interpreting this as an upper limit to emission for a 15km blackbody leads to a value of $T < 2.5 \times 10^6$ K, consistent with current theory. It should be noted, however, that a hot young neutron star is most unlikely to be radiating as a uniform temperature blackbody. The optical properties of the surface as well as the strong magnetic field, are likely to cause significant departure from a Planck function spectral form (Brinkman 1980); for realistic parameters, these departures should be a factor ~2 (Cheng and Helfand 1983). In addition, the magnetic field introduces an anisotropic thermal conductivity in the surface layers of the star leading to a surface temperature distribution significantly hotter at the magnetic poles than at the magnetic equator (Greenstein and Hartke 1982). This will introduce a modulated component to even a purely thermal X-ray flux, further complicating the interpretation of the data. The most conservative expression of the Crab results, then, is that they are not inconsistent with current predictions from cooling theory.

As noted in the introduction, a point source of X-rays has now been seen to be coincident with the Vela pulsar. Interpreting the total point source flux as surface blackbody emission yields a temperature of $\sim 9 \times 10^5$ K for this $\sim 10^4$ year old star, again consistent with current theoretical estimates. However, this emission is not modulated at the pulsar rotation period to less than the 1% level. For the reason cited above, this is difficult to understand if the emission arises from the stellar surface. Using the modulated flux to establish a temperature upper limit leads to a value of $T \lesssim 3 \times 10^5$ K ($L_x \lesssim 10^{31}$ ergs s^{-1}), substantially below that expected unless rapid early cooling from a pion condensate core is important. A critical observation for future X-ray missions will be the determination of the spectrum of the Vela point source emission over as wide an energy range as possible to help separate nonthermal and thermal components and establish the actual temperature of the pulsar surface.

The only other known radio pulsar associated with a SNR is the source first discovered as a 150 msec X-ray pulsator in MSH 15-52 (Harnden and Seward 1982). The age of this object is somewhat uncertain, since the SNR age ($\sim 10^4$ yr) and pulsar spin down time (~1500 yr) are in substantial disagreement. Nonetheless, the object is clearly young and provides another important test of neutron star cooling theory. The X-ray luminosity in the <u>Einstein</u> band is $L_x \sim 5 \times 10^{34}$ ergs s^{-1} and the signal is ~100% modulated with a single pulse of FWHM ~25% each period. The single radio pulse is considerably narrower, with a FWHM ~9% (Manchester <u>et al.</u> 1982); the relative phase of the pulses has not yet been determined. This situation is in marked contrast to the Crab pulsar for which the radio and X-ray pulse profiles are quite similar. Interpreting the total flux from this source as surface thermal emission yields $T \sim 2.5 \times 10^6$ K. Greenstein and Hartke (1982) have attempted to model the X-ray pulse profile with an inhomogeneous surface temperature distribution. They require a magnetic polar cap temperature of $T \sim 9 \times 10^6$ K and a (perhaps implausibly) high pole-to-equator temperature ratio to fit the data. If this interpretation is correct, the pulse width and modulation fix the angle between the magnetic and rotation axes at ~40°. The high temperature required, however, may imply a source of polar cap heating (§2.1) or a nonthermal emission component (§1.3) and the implications of this object for neutron star cooling theory remain unclear. Again, spectral and polarimetric data, attainable with an AXAF-scale facility, are crucial for further progress.

2.2 Initial Cooling - A SNR Search

The galactic supernova rate and pulsar birthrate are now in approximate agreement (Lyne, Manchester, and Taylor, this volume), suggesting that a significant fraction of supernovae leave behind a neutron star. Most, if not all, of these objects must be radio pulsars, although perhaps only 1 in 5 will be detectable at radio frequencies owing to the narrowly beamed emission. One anticipated result of the *Einstein* survey of SNR was that a number of such hot young neutron stars would be discovered. This has not turned out to be the case.

A total of 72 galactic SNR were mapped with the imaging instruments on *Einstein*; 33 of these were within 5 kpc and any central neutron star with $T \gtrsim 1.5 \times 10^6$ K would have been easily seen (NB - A high neutron star velocity will not remove it from the remnant's center for $\sim 10^4$ yr since the average remnant expansion velocity over this time (~500 km s^{-1}) is considerably greater than the average measured pulsar transverse velocity of ~150 km s^{-1}). A total of twelve X-ray point sources associated with these remnants were detected (see Helfand and Becker 1982 for a complete review of these data). Briefly, four are in Crab-like remnants (the Crab, Vela, 3C58, and CTB80), two are X-ray binaries (SS433 and G109.1-1.0), one is MSH15-52, discussed above, and three are seen in large angular diameter remnants and are likely to be chance superpositions of foreground or background objects (W28, PKS1209-56, and G127.1+0.5). This leaves two sources, one of which is very distant and about which little is known (Kriss, private communication), and the other of which is in RCW 103 (Tuohy and Garmire 1980). This latter source is located precisely at the center of a 1-3000 yr old remnant and has no optical counterpart brighter than $m_V \sim 22$, implying $L_{opt} < 10^{-2.5}$ that of the Crab pulsar optical luminosity (Tuohy *et al.* 1982). The limit on radio pulses is similarly $\sim 10^{-2}$ that of the Crab. The source is too weak for an effective search for X-ray pulsations. A blackbody interpretation leads to a surface temperature estimate of $\sim 2 \times 10^6$ K, consistent with standard cooling theory.

Apart from the two binary sources, RCW103 contains the only X-ray point source seen in any young ($<10^4$ yr) shell-type SNR. This lack of detections may be the most significant datum to emerge from the search for cooling neutron stars. Of the seven historical remnants (Cas A, Kepler, Tycho, 3C58, the Crab, SN1006, and SN185-

RCW86), only the two Crab-like objects contain point sources. For SN1006, the limit on thermal emission is particularly severe; $T < 5 \times 10^5$ K for a neutron star anywhere within the inner 20' of the remnant (Winkler, private communication). For the other objects, the limits range from 1-2 × 10^6 K. We are forced, then, to one of three conclusions: 1) current cooling calculations are in error for standard neutron star models; 2) the neutron stars in these remnants contain exotic species which lead to faster early cooling; or 3) that a substantial fraction of supernova do not leave neutron stars. For the putative Type I remnants of Kepler, Tycho, and SN1006, the latter conclusion is in agreement with the majority view amongst modellers of SN explosions (see Wheeler 1982 for a review). For Cas A and others of the dozens of remnants surveyed, however, conclusion 3 again raises the question of whether or not there are enough classical SN in the Galaxy to produce the observed number of radio pulsars. Further evidence on this point is presented in §4. A decision on whether conclusion 1 or 2 are important will have to await further observations of the known young neutron stars discussed above.

2.3 Magnetospheric Emission

An X-ray image of the Crab Nebula is dominated by the bright point source centered on the pulsar. These X-rays are ~100% modulated at the stellar rotation frequency and the pulse morphology is generally similar in form and phase to the emission at radio wavelengths. Important differences exist, however, between the radio and higher energy pulses, suggesting a different emission mechanism is responsible. There is a break in the spectrum between the radio and the optical/X-ray pulses and the brightness temperature of the latter is low enough that incoherent processes suffice to explain the observed intensity. In addition, unlike the radio pulses, the higher frequency radiation is not time variable and there is no observed counterpart to the "giant pulses" outside the radio band.

Shklovskii (1970) was the first to suggest that incoherent synchrotron radiation far from the stellar surface was responsible for the optical (and higher energy) pulsed radiation. Adopting this idea, Pacini (1970) pointed out from fairly general considerations that a pulsar's optical luminosity should scale as $L \quad B_0^4 P^{-10} \quad P^{-8} \dot{P}^2$, where B_0 is the star's surface magnetic field strength derived assuming that rotational braking results exclusively from magnetic dipole radiation and a purely dipolar field geometry applies. The discovery of 25th magnitude optical pulses from the Vela pulsar (Wallace et al. 1977) supported this conclusion. The ratio of the Crab ($P = 0.033$s, $\dot{P} = 4.21 \times 10^{-13}$ ss^{-1}) pulsed X-ray luminosity to the point source component of the Vela ($P = 0.089$ s, $\dot{P} = 1.25 \times 10^{-13}$ ss^{-1}) X-ray emission also approximately agrees with this scaling law; the problem, of course, is that the Vela X-rays are not pulsed. For the other young pulsar in MSH 15-52 ($P = 0.15$ s, $\dot{P} = 1.5 \times 10^{-12}$ ss^{-1}), the X-ray emission does not scale to the Crab X-ray luminosity following this relation, exceeding the nominal ratio by a factor of ~10^3, although the fraction of the rotational kinetic energy loss that emerges as pulsed X-rays is approximately the same for the two sources ($L_x/\dot{E} \sim 10^{-4}$). Unlike the Crab, however, the X-ray pulses from MSH15-52 have a shape that differs substantially from the radio pulse morphology and, as we have suggested above, may contain a significant thermal component.

The Crab pulsar, then, remains the only clear example of non-thermal magnetospheric emission in the X-ray band. Other candidates from the list of SNR/point source associations cited above include the centrally located objects in the Crab-like remnants 3C58 and CTB80, and RCW 103. All are too weak to perform a meaningful pulsation analysis; Tuohy _et al._ (1982) have argued against this interpretation for RCW 103 on the basis of an L_x/L_{opt} ratio which differs from the Crab by a factor of $>10^2$. It is interesting to note that in the other historical SNR, the limits on pulsar emission expressed as a fraction of the Crab luminosity are now more stringent in the X-ray band than at radio frequencies, reaching $<10^{-5}$ L_{Crab} for SN1006. Limits for the remaining sample of older remnants are typically $\sim 10^{-3}$ L_{Crab}. However, the much steeper period dependence of the high energy emission suggests that this is not a very serious constraint on the population of young pulsars in SNR.

3. X-RAYS FROM OLD PULSARS

After 10^4-10^5 yr a pular is expected to have cooled to less than a few hundred thousand degrees and to have spun down to the point where high energy magnetosphere emission is insignificant. Several other processes, however, still operate to keep the star warm enough to emit X-rays. A measurement of, or limit on, the level of this emission can thus be an important constraint on models for pulsar magnetospheres and neutron star interiors.

3.1 An X-Ray Survey of Radio Pulsars

To exploit this diagnostic, we conducted a survey of nearly two dozen radio pulsars using the imaging instruments on _Einstein_. The objects were chosen to be nearby ($\lesssim$ 1 kpc) and/or to have properties expected to maximize a particular X-ray heating effect (e.g., low period, high magnetic field, etc.). The radio position errors were all <30" and typically $\lesssim$ 1". All sources were first observed with the imaging proportional counter (IPC) for exposures of ~2,000 to ~20,000 s, implying flux thresholds in the 0.10-3.5 keV band of $\sim 10^{-13}$ ergs cm^{-2} s^{-1}. The log N-log S relation for IPC sources predicts ~2 sources per square degree above this level. Taking a generous 90" error circle radius for the X-ray positions, we have thus searched a total of $\lesssim$ 0.05 square degrees in the survey, implying that $\lesssim$ 1 serendipitous X-ray source should have appeared coincident with a pulsar position by chance. A total of eight sources were detected. The one with the largest position error was subsequently identified as an AGN (Margon, Chanan, and Downes 1981) (the one statistically expected spurious source); we are confident that the remaining seven sources represent the detection of X-ray emission from radio pulsars. In addition to the three objects cited above (Crab, Vela, and MSH15-52), they include PSRs 0355+54, 0950+08, 1055-52, 1642-03, and 1929+10; their IPC counting rates are, respectively, ~0.01, 0.008, 0.10, 0.01, and 0.006 ct s^{-1}. The five older objects have spin down ages ranging from ~5×10^5 to ~10^7 yr; all have periods less than 0.4 s, more than a factor of 2 below the median for all pulsars.

Three of the objects were subsequently observed with the HRI to obtain higher spatial resolution and better positional accuracy. For PSR 1929+10, a source with a counting rate of 0.0007±0.0002 ct s^{-1}, centered on the radio position (±2"), was detected. The resulting IPC/HRI ratio of 8±3 was consistent with the moderate-energy IPC pulse height spectrum. We conclude that this pulsar is a point source of X-ray emission and discuss the implications below. In the case of PSR 1642-03, no source was detected in either of two long HRI exposures totally >30,000 s, one of which was taken within hours of an IPC pointing that showed a 5 σ source coincident with the radio position and unchanged in intensity from an observation 18 months earlier. The implied IPC/HRI ratio for a point source, >25, is inconsistent with the soft IPC pulse height spectrum in which $\gtrsim$ 75% of the counts fall below 1.5 keV. In this case we conclude that the source is extended on a scale of ~90", implying a surface brightness too low for detection with the HRI but consistent with a point source for the IPC. The HRI pointing for PSR1055-52 also showed evidence of extent on a scale of ~10" (Cheng and Helfand 1982). Finally, the IPC source associated with PSR 0355+54 consisted of an elongated region of emission 5' long with the pulsar at one end.

A search for pulsations was carried out for three of the sources. Barycentric corrected photon arrival times were folded at the radio pulsar period; in each case, errors in the measured values of P and $\dot{P}$ led to a phase drift of $<10^{-2}$ P over the length of the observation when extrapolated to the epoch of the X-ray data. The limits on any modulation are <30% and <3% for PSRs 1642-03 and 1055-52, respectively (the two extended sources), and <25% for the point-like source PSR 1929+10.

In addition to the detections, we obtained stringent upper limits on ~20 other pulsars with the IPC. In particular, observations of 10 sources lying within 500 pc led to X-ray luminosity limits of between 0.5 and 5×10^{30} ergs s^{-1}, implying blackbody temperature limits of between ~3 and 5×10^5 K. Below, we outline briefly the implications of these point source limits and the detections of PSR 1929+10 and Vela for various pulsar heating models.

3.2 Heating Mechanisms

The radio pulse emission mechanism and the structure of the pulsar magnetosphere are problems which have proven remarkably resistant to solution over the past 15 years. A currently popular class of models predicts significant heating of the magnetic polar cap by electrons or positons flowing back toward the star after having been accelerated in the pair production discharge of the outer magnetosphere (Cheng and Ruderman 1980; Arons 1981 [hereafter CR and AS]). The predicted X-ray luminosities from the hot polar caps ($\sim 10^{10}$ cm^2) range from 10^{26}-10^{31} ergs s^{-1} depending on such parameters as the pulsar's period, radius, and surface magnetic field strength. This emission should be modulated at the pulsar rotation period, although the depth of the modulation depends on the thermal conductivity of the stellar surface and the relative orientation of the rotation and magnetic axes (Greenstein and Hartke 1982). For PSR 1929+10, the models predict $L_x \sim 3 \times 10^{28}$ (CR) and $L_x \sim 8 \times 10^{28}$ (AS) ergs s^{-1}. Adopting a distance of 65 pc, the X-ray data imply a luminosity of $L_x \sim 6 \times 10^{28}$ ergs s^{-1}; the limit on the modulated flux yields $L_x \lesssim 2 \times 10^{28}$ ergs s^{-1}. These values are not inconsistent with the predictions (which have come down by 2-3 orders of magnitude over the past few years), but imply that little or no pair production can occur in the outer electrostatic gap of the AS picture. For Vela, the predictions are $L_x \sim 2 \times 10^{31}$ (CR) and 2×10^{30} (AS) ergs s^{-1}. The observed luminosity from the point source is $\sim 3 \times 10^{32}$ ergs s^{-1} although the modulated component is $\lesssim 1\%$ of this value. The RS model requires synchrotron cooling of the backflowing electrons to meet this latter limit. Perhaps the most difficult problem these models face for Vela, however, is the fact that the modulated X-ray flux is $<10^{-4}$ of the gamma-ray flux which is thought to arise from one sign of the cascading pairs as the other flows back to heat the stellar surface. A solution may be found either through alternative magnetospheric models or from a detailed analysis of the heat transport in the stellar crust which might spread the energy of the cap's bombardment more evenly over the star, reducing the X-ray modulation.

The magnetic field of a neutron star is tied to the solid crust, and the electromagnetic braking torque acts directly on this outer component to slow the rotation. The core is largely superfluid neutrons, and the details of the boundary between these two components has been a matter of considerable interest. The strength of the coupling will determine the degree of differential rotation expected and, in turn, the amount of frictional heating which will occur at the crust/core interface. One critical question is whether or not the superfluid vortices of the core pin to crustal nuclei. A calculation of heating under the assumption of no pinning has been carried out by Harding *et al.* (1978). The predicted temperatures are primarily a function of stellar mass owing to the changing ratio of crust and core mass fractions; less massive stars have much thicker crusts implying lower heating rates from the more rapidly spinning core. The X-ray flux from PSR 1929+10, if interpreted as emission from a blackbody of radius 15 km, implies a temperature of $\sim 2 \times 10^5$ K (the spectrum is inconsistent with such a low temperature, however). This limit on the thermal luminosity of this source as well as the undetected objects, would imply masses of $<0.5\ M_{\odot}$ for these pulsars. This is to be contrasted with the observed neutron star masses in a number of X-ray and radio binary pulsars which cluster around $1.4\ M_{\odot}$. A more likely conclusion is that some vortex pinning does occur. Recently, Alpar et al. (1983) have investigated the question in detail and have calculated heating rates that depend on P, $\dot{P}$ and the properties of the boundary layer. The only two pulsars in our survey that should be detectable under these assumptions of fairly strong pinning are PSR 0950+08 and PSR 1929+10, both of which were seen; these were also the only two sources for which no evidence of spatial extent are adduced. The X-ray luminosity of these sources constrains the details of the pinning model, offering an important new diagnostic for the interior dynamics of neutron stars (Helfand 1983).

Another potential source of heat in all neutron stars is the release of energy accompanying the sudden speed up in rotation rate observed as a "glitch." Vela is by far the most active source in this regard with a total of six events ($\Delta P/P \sim 10^{-6} - 10^{-7}$) in the last 12 years. The Crab has undergone two or three much smaller spinups ($\Delta P/P \sim 10^{-9}$) and Vela-sized glitches have been observed once each in three older sources (see Alpar and Ho 1983 for a recent summary). In addition, nearly all pulsars exhibit some degree of "timing noise" indicating small irregular changes in rotation rate (e.g., Helfand et al. 1980). The amount of energy released in these events depends critically on the mechanism responsible. An early model for the Crab (and Vela) glitches postulated sudden cracks in the neutron star crust (or core) with an accompanying release of gravitational and strain energy amounting to $10^{40} - 10^{45}$ ergs per event (Ruderman 1969; Baym and Pines 1971; Pines et al. 1972). More recently, a scenario involving the sudden unpinning of the superfluid vortex lines has been advanced (Anderson and Itoh 1975; Alpar et al. 1981); such an event would release considerably less energy than a starquake (only $\sim 10^{39}$ ergs for a Vela sized glitch).

To the extent that energy released in a glitch is thermalized and eventually radiated away in photons from the stellar surface, the temperature limits imposed by these X-ray data constrain glitch models. For example, in PSR 1929+10, the observed luminosity of $\sim 6 \times 10^{28}$ ergs s^{-1} implies an energy input from glitches of $<2 \times 10^{36}$ ergs yr^{-1}. If each event deposits a total energy of $\gtrsim 10^{39}$ ergs, the events must be separated by $\gtrsim 500$ yrs. This is approximately the observed rate for old pulsars (Alpar and Ho 1983). For Vela, the X-ray data allow a choice between the two models. The total point source X-ray luminosity is $\sim 3 \times 10^{32}$ ergs $s^{-1} \simeq 10^{40}$ ergs yr^{-1}. There has been one glitch every two or three years since the pulsar's discovery and thus, to balance the radiated energy there must be $<3 \times 10^{40}$ ergs per event released as thermal energy in the star. This is only 10^{-4} of the total energy associated with a corequake but is consistent with the unpinning picture. Coupled with the evidence in favor of a pinned superfluid component derived from the crust-core coupling arguments presented above, these data offer strong support to the emerging picture of the superfluid behavior in pulsar interiors and the interaction of this component with the remainder of the star.

4. X-RAY SYNCHROTRON NEBULAE

Left to consider is the detection of extended X-ray emission from radio pulsars. The Crab Nebula is, of course, the archetype of an extended region of synchrotron radiation driven by particles accelerated by a central pulsar. Before the launch of Einstein, it was the only such object known to emit X-rays, although several other radio supernova remnants had been identified as analogous objects from their centrally peaked brightness distributions, flat radio spectra, and high linear polarization. Several of these Crab-like remnants have now been detected as X-ray sources (Wilson 1980; Becker et al. 1982) and in two cases, a central point source (presumably the driving pulsar) is seen. In addition, we have detected such nebulae around six radio pulsars including the Crab, Vela, MSH15-52, PSRs 1055-52, 1642-03, and 0355+54. They range in age from ~10^3 to ~10^6 years, and in luminosity from 2×10^{37} ergs s^{-1} to 6×10^{31} ergs s^{-1}. Seward (the volume) has discussed the younger three sources and a detailed argument concerning the case for synchoton nebula around PSR1055-52 has been given by Cheng and Helfand (1983).

A general scenario for the origin and evolution of these nebula can be found in Helfand (1983). Briefly, we adopt the pair production discharge magnetospheric models cited above and use the observed intensity and spectrum of the pulsed gamma-rays from the Vela pulsar to define the parameters of the particles injected into the surrounding magnetic field. The nebular field strength is constrained by two considerations: 1) the maximum potential drop (and, thus, the highest particle energy) which can occur in the magnetosphere coupled with limits on diffuse gamma emission from the vicinity, and 2) by the reflection of the turnover of the particle spectrum implied by the lack of pulsed X-ray emission in the turn over in the diffuse radiation spectrum between the X-ray and optical regimes (i.e., no optical nebula is seen). The size of the nebula is derived from the requirement of pressure balance between the expanding bubble of particles moving outward at the Alfven speed and the thermal pressure of the surrounding medium (Blanford et al. 1973). The observed properties of the Vela nebula are well matched by this picture; extrapolating to lower fields and particle luminosities can yield substantial agreement with the sizes and luminosities of the older pulsar nebulae as well.

The detection of X-ray synchrotron nebulae around a number of radio pulsars provides important new information on magnetospheric particle acceleration models, gamma-ray emission mechanisms, evolution of the particle flux, and the contribution of pulsars to the electron cosmic ray and diffuse gamma-ray backgrounds. Most importantly, however, the detection of every object above the value of BP^{-2} at which the outer gap particle acceleration mechanism is supposed to cease (and the nondetection of every source below this value) strongly suggests that X-ray synchrotron nebulae are a necessary consequence of an active young pulsar. This conclusion holds important implications for the pulsar/SNR association problem. These nebulae are almost certainly isotropic and, as such, should be visible within any SNR which contains an active pulsar. The nebula surrounding PSR 1055-52 (a $\sim 5 \times 10^5$ yr old source) is sufficiently luminous to have been detected in any of the many remnants surveyed out to 4 kpc, and a Vela-type nebula ($t \sim 10^4$ yr) could have been seen to twice that distance. The only new synchrotron nebula found, however, was the one surrounding the newly identified pulsar in MSH15-52. We are thus forced to conclude either 1) that the majority of SN which produce remnants do not create neutrons stars, or 2) that the pulsar phenomenon does not turn on in at least some sources for $>10^4$ yr (i.e., after the SNR is dissipated or the pulsar has moved away). If we adopt 1) we must search for new sites of neutron star formation; if 2) is correct, it could tell us much about the pulsar emission process (Radhakrishnan and Srinivasan 1980) and/or the generation of neutron star magnetic fields (Blanford _et al._ 1982).

5. SUMMARY

We have presented a review of the X-ray data currently available on the longest-lived remnant of a supernova explosion - the neutron star - and have summarized the implications these data hold for problems in pulsar physics and neutron star evolution. There is still no definitive detection of thermal emission from the surface of a young neutron star, although the few candidate examples and stringent upper limits now available have led to significant advances in cooling theories. The Crab pulsar remains the only clear example of nonthermal magnetospheric X-ray emission and the bewildering array of behavior seen in other young pulsars and Crab-like remnants suggests further work on the high energy pulse emission process is needed. Several older radio pulsars have been detected for the first time outside the radio band; the pulsar survey observations offer important new constraints on models of polar cap heating, crust-core coupling and glitches. The unexpected discovery of synchrotron nebulae around a number of objects offers new information on the evolution of particle acceleration in the magnetosphere and holds important implications for the origin of galactic neutron stars.

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DISCUSSION

WINKLER: How bright would you expect the synchrotron nebula around the Vela pulsar to be optically? Shouldn't it be detectable?

HELFAND: Extrapolating from 0.2 keV to 2 eV using a Crab-like spectrum (similar to the observed X-ray power law spectral index) yields an integrated magnitude of $m_v \sim 17$ or $m_v \sim 27$/sq arcsecond. However, a turnover in the injected electron spectrum may well leave it substantially below this value. We have proposed for time at Cerro Tololo to observe several of these X-ray nebulae for optical counterparts.

BENFORD: Your analysis is thoroughly married to the Cheng-Ruderman and/or Arons-Scharlemann models. These have had to recant and adjust their pulsed X-ray luminosity by 1,000 to escape the constraints of observation. Also, it seems outer gaps might have trouble giving sharp pulses in X-ray and gamma-ray. In view of this, shouldn't you consider other ways to connect with the nebular parameters - say a larger B?

HELFAND: Yes, but I think the essential point is that particules accelerated by the pulsar are producing an X-ray synchrotron nebula. I have presented one possible more detailed scenario, but I am sure there are others. The one point in favor of gap models (or at least consistent with them) is that pulsars with values of $B_{12}P^{-2} \lesssim 10$ do not produce such nebulae whereas all those with $B_{12}P^{-2} > 10$ do, as the theory would predict.

SALVATI: a) In the Vela X-ray Nebula, the emitting particles must be reaccelerated. Then one should expect no relation between the nebular spectrum and the gamma-pulsar spectrum.
b) As for PSR 0355, you postulate very high energy particles, capable of emitting in the gamma-ray range before leaving the pulsar neighborhood. Has the gamma-ray emission been observed?

HELFAND: a) I am not sure there should be no relation, but I agree I have oversimplified things considerably.
b) My scenario does indeed require that all of these pulsars with nebulae should be gamma-ray sources and none but the Crab and Vela have been detected. The predicted fluxes are a factor of ~10-100 below the COS-B upper limits for PSR 1055-52, PSR 0355-154 and PSR 1642-03 but should be detectable with GRO.

MANCHESTER: Some models suggest that the gamma-ray pulses from the Vela pulsar are generated by the inverse Compton radiation. If this is true, what would be the implications for your model?

HELFAND: I have been chastened before by one of my colleagues to refer to my description of these nebulae as a "scenario" rather than a model and have taken the suggestion to heart. As Dr. Salvati has already mentioned, the requirement for particle reacceleration in the Vela Nebula (but not, I might note, for the other sources), may well destroy any relationship between the pulsed gamma-ray and X-ray spectra; an alternative to curvature radiation as the production mechanism for the gamma-ray pulses would do the same.