UNPULSED X-RAYS FROM PULSARS

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I. INTRODUCTION

The radio emission from pulsars is energetically insignificant, yet its distinctive character led to their discovery and subsequent identification with rotating magnetized neutron stars. In the intervening thirteen years, a wealth of radio data have been accumulated from which we have learned something of the magnetospheric properties, stellar structure, and evolutionary history of these objects. Yet we still do not know how pulsars pulse, what the neutron star interior is like or, with certainty, how and where pulsars are formed. And, we have not yet 'seen' a radio pulsar, in the sense that we see other stars, i.e., by detecting thermal photons from its surface. The Einstein Observatory soft X-ray telescope offers a new opportunity to attempt such an observation. We report herein the preliminary results of several programs aimed at the detection of thermal X-ray emission from isolated neutron stars.

To begin a search for neutron star surface thermal emission one must choose the appropriate spectral regime; given the narrow range of expected neutron star radii, this is equivalent to choosing a range of stellar temperatures. For $T \lesssim 3\mathrm{x}10^4$ K we find that optical and infrared instrumental sensitivities fall far short of being able to detect even the closest known pulsars ($m_V \gtrsim 27$). In the ultraviolet ($3\mathrm{x}10^4$ K < T < 10^5 K) limitations of both instrumental capabilities and the high opacity of the interstellar medium render detection extremely unlikely (Greenstein et al. 1977). We already know that pulsars have temperatures of < $3\mathrm{x}10^6$ K from their non-detection in the 2-10 keV all-sky surveys carried out earlier in this decade (Greenstein and McClintock 1974). We are left, then, with the hope of detecting pulsar thermal emission in the soft X-ray regime, and it is in this temperature domain of $2\mathrm{x}10^5$ K < T < $2\mathrm{x}10^6$ K that the Einstein Observatory is uniquely sensitive (Helfand et al. 1980).

Thus limited by the observational constraints, what theoretical justification makes a soft X-ray survey of pulsars desirable? There are

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in fact, several reasons we expect to find the temperatures of isolated neutron stars in the range of a few hundred thousand to a few million degrees; these have been reviewed in detail elsewhere (Helfand et al. 1980). Briefly, they include: residual heat of formation (the star is still cooling from its initial temperature of $\sim 10^{10}$ K), polar cap heating (resulting from bombardment by relativistic particles streaming back onto the stellar surface from magnetospheric pair-creation regions), dynamical friction (whereby energy extracted from the more rapidly spinning core is deposited in the crust), starquakes (which release large amounts ($\sim 10^{40}$ erg) of crustal strain energy per event), accretion of material from the interstellar medium, and other, as yet unspecified processes (which are perhaps the most likely sources of heating in the stars we detect). Calculations involving each of these mechanisms lead to temperature predictions in the range to which we are sensitive; thus observation of, or upper limits on, the thermal emission from pulsars derived from Einstein observations can provide important constraints on theories of pulsar emission mechanisms, and neutron star structure and evolution.

II. YOUNG NEUTRON STARS AND SUPERNOVA REMNANTS

II.1 Cooling Stars

The Einstein pulsar surveys are divided into two main categories: 1) a search for cooling neutron stars in young supernova remnants (SNR) where the emission derives from a reservoir of thermal energy left over from the star's formation and 2) a survey of selected radio pulsars wherein the emission is expected to arise from the conversion of the star's rotational kinetic energy to heat. Nearly fifty SNR including all seven historical remnants have been observed to date with the imaging instruments onboard the Observatory (see Helfand 1981 for a review). Searches for point source emission at the remnant centers have been undertaken for most of these objects using either the imaging proportional counter (IPC - 1' resolution) and/or the high resolution imager (HRI - 5" resolution; see Giacconi et al. 1979 for a complete description of the instruments). In only four cases is any enhancement above the nebular background detected. Prior to these observations, temperature predictions from neutron star cooling calculations ranged from $3.5\text{-}15\times10^6$ K for a 300-year-old star to $2\text{-}5\times10^6$ K after 10^3 to 10^4 years (see Tsuruta 1979 for an extensive review of pre-Einstein calculations). Hot neutron stars in any of the historical remnants and in a large number of the older objects would have been easily detectable at these temperatures.

In Table 1, we present apparent temperatures and upper limits for neutron stars in the historical remnants along with a sampling of the older objects (see Helfand et al. 1980 for details and references). These results admit but two possible conclusions: either the majority of supernovae which leave remnants do not produce neutron stars or the cooling calculations are in need of substantial revision. Stimulated by the new observations, a number of groups (Glen and Sutherland 1979, 1980;

Table 1

Limits on Thermal Emission from Neutron Stars in SNR

Remnant	Age (yr)	Temperature (10^6 K)
Cas A	∿ 300	< 1.5
Kepler	376	< 2.0
Tycho	408	< 2.0
SN 1006	974	< 0.7
RCW 86	1795	< 1.5
W 28	∿ 3400	< 1.8
G 350.0-1.3	∿ 8000	< 2.0
G 22.7-0.2	∿ 10^4	< 2.2
	Possible Detections	
3C 58	795	——
Crab	926	2.0
RCW 103	∿ 2000	2.2
Vela	∿ 10^4	1.5

Lamb and van Riper 1980; Tsuruta and coworkers [this volume]) have reinvestigated the cooling problem. Owing to the inclusion of the appropriate relativistic thermodynamics and updated high energy and nuclear physics parameters, the new calculations predict substantially lower temperatures for standard neutron star equations of state. In no case, however, can the models explain the low limit on the temperature of a hypothetical neutron star in SN 1006 unless exotic neutron star interiors (pion condensates or quarks) are invoked; the limits for Cas A and Tycho are very near the lower bound of predicted temperatures.

While these limits, then, have been valuable inputs to work on cooling theory, the actual detection of a hot young neutron star would be even more important. In four cases, there are point X-ray sources at the center of SNR; however, in each instance, the identification of this emission with thermal flux from the stellar surface is uncertain. For the Crab, a bright point source is seen at the position of the pulsar. However, as had been known from earlier lunar occultation experiments (Wolff et al. 1975; Toor and Seward 1977) the majority of this flux is pulsed and, presumably, of nonthermal origin. Recent time-resolved images of the Crab obtained by Harnden et al. (1979) show that the X-ray emission persists throughout the rotation period, reaching a minimum of ∿ 1% of the peak flux about 40° before the main pulse. If interpreted as thermal emission from the surface, the implied temperature of the neutron star in the Crab would be ∿ 2×10^6 K. Unfortunately, data from the instrument with sufficient spatial resolution to separate the point source from the surrounding nebular emission contain no energy information, so the spectrum of this possible unpulsed component cannot be ascertained. In light of the results reported by Smith (this volume) on the persistence of optical synchrotron emission throughout the Crab pulse period (with a peak-to-minimum ratio very similar to that seen in the X-ray), it seems safest to regard the two million degree temperature as an upper limit rather than a detection of thermal emission.

For the only other known pulsar associated with a SNR, Vela, the situation is similarly ambiguous. What appeared as an unpulsed point X-ray source associated with the pulsar at 1' resolution in an image obtained with the IPC breaks up into an extended component surrounding a central point in the HRI data (Harnden 1980) This nebula has a power law spectrum with a slope similar to that of the Crab although it is $\sim 10^4$ times less luminous and ~ 5 times smaller in linear extent. Again, the spectrum of the central source (which is point-like at 5" resolution) is not separable from that of the surrounding nebula and, although the emission is unpulsed, the identification of the radiation with thermal surface emission remains uncertain; the quoted temperature of $1.5\text{x}10^6$ K for a 10 km star is again most safely interpreted as an upper limit.

In the case of the young southern SNR RCW 103, Tuohy and Garmire (1980) have detected a point source at the center of the radio and X-ray emitting shell. It is too weak for spectral or temporal information to yield clues to its origin and no radio pulsar is seen at the location (Manchester, private communication). If interpreted as thermal emission, a temperature of $2.2\text{x}10^6$ K is indicated.

The final example of a point X-ray source/SNR association is 3C58, the probable remnant of SN 1185. The remnant's morphology is very similar to that of the Crab (centrally condensed, filamentary, and highly polarized); the IPC X-ray image shown by Chevalier at this conference is also reminiscent of the Crab with a strong degree of central condensation. Becker (private communication) has found a possible point source at the center using the HRI but, again, spectral and temporal data are not available. In summary, then, the search for thermal emission from hot young neutron stars in SNR has been notably unsuccessful with four possible (and no certain) examples out of fifty remnants examined: either we are looking in the wrong place or the young neutron stars are quite cool.

II.2 Synchrotron Nebulae

The SNR imaging results supply an independent piece of evidence which suggests the former conclusion is correct. In the two cases where we know young neutron stars exist, the Crab and Vela, we see not only X-ray point sources but extended X-ray synchrotron nebulae as well. We would have easily detected such a nebula with the Vela luminosity in any of the historical remnants and none are seen. The Crab pulsar is one tenth the age of Vela and is losing rotational energy at rate $\dot{E} \sim 100\ \dot{E}_{Vela}$; its synchrotron nebula is appropriately brighter and larger. It seems reasonable to assume that all rapidly rotating, magnetized neutron stars (i.e., young pulsars) will create such nebulae, and that the X-ray luminosity of these nebulae will scale with the driving pulsars' value of $\dot{E}$ to some power n. From the only two examples available we find $n \approx 2$. (This value is consistent with the lack of detection of any such nebulae around older, nearby radio pulsars which requires $n > 1$). Thus, we may set a limit on $\dot{E}$ for a hypothetical neutron star at the center of any remnant. In particular, for the historical remnants with ages comparable to or younger than the Crab, the limits on $\dot{E}$ are 10^{-2} to 10^{-3} $\dot{E}_{Crab}$. Such objects may exist, but they cannot be the majority of pulsar progenitors, since the P-$\dot{P}$ distribution of observed radio pulsars would be substantially different if a large number of objects were born with long periods and/or small values of $\dot{P}$. The X-ray results, then, argue strongly that five of the seven historical remnants and a large majority of the other remnants with ages $< 10^4$ yr do not contain radio pulsars, independent of arguments concerning the beaming factor for pulsar radio emission. If this conclusion is substantiated by the considerable work in progress, it serves to exacerbate the already troublesome discrepancy between the pulsar birthrate and the rate of supernova explosions in the Galaxy, and some quieter mechanism for producing pulsars may have to be devised.

III. RADIO PULSAR SURVEY

The second major facet of the Einstein Observatory's pulsar program consists of a survey of known radio pulsars. Designed to test the numerous heating mechanisms required by various theories of pulsar emission and neutron star structure, the program consists of an unbiased survey of all known pulsars within 300 pc coupled with a selective search of about a dozen objects chosen for short periods, large $\dot{E}$, large amplitude timing noise, etc., which will most tightly constrain existant models. To date, eighteen pulsars have been observed to a limiting X-ray flux [0.15-4.5 keV] of $\sim 1 \times 10^{13}$ erg cm^{-2} s^{-1}. The radio positional error boxes range from 1 square arc second to rectangles 1'x20', while the uncertainty in the position of a detected X-ray source is a circle of radius $\sim$ 1' for IPC observations and 5" for HRI data. In all, $\sim$ 0.04 square degrees of radio error boxes have been searched. Above 10^{-13} erg cm^{-2} s^{-1}, the IPC log N-log S relation predicts 1.5 sources per square degree; thus, we have a $\sim$ 10% probability of finding one chance source coincident with a pulsar position. Six have been detected. Along with the stringent upper limits derived from the remaining objects, these data severely constrain several of the models for pulsar behavior noted above.

The first pulsar detected was the nearby object PSR 1642-03 (Novick et al. 1979). The IPC X-ray position is 44"±60" from the well determined radio location; an HRI observation has been scheduled to confirm the identification. The source flux is $(2.6 \pm 0.3) \times 10^{-13}$ erg cm^{-2} s^{-1} and, along with the limited spectral information which shows a very soft spectrum and little evidence for interstellar absorption, is consistent with the emission arising from a blackbody of radius 16 km at a temperature of 3×10^5 K. The upper limit to modulation of the X-ray signal at the radio pulsar period is $\lesssim 30\%$. For a distance of 160 pc (Taylor and Manchester 1975) the X-ray luminosity is 8×10^{29} erg s^{-1} yielding values for the ratio of X-ray-to-radio output $L_x/L_r \sim 4000$ and a model-independent ratio of rotational energy loss to X-ray luminosity $\eta = L_x/\dot{E} \sim 0.07\%$. These numbers can be used, for example, to set a limit on the crust-core coupling in this star (Harding et al. 1978) or to establish the minimum interval between starquakes which generate heat pulses of $\sim 10^{39}$ ergs -- they must be less frequent than once every 400 years if the thermal energy leaves the star at a more or less constant rate. If the emission arises primarily from a hot polar cap, the temperature of the cap would be $\sim 10^6$ K and the measurement can be used to set an upper limit on the parameter ε in the Cheng-Ruderman-Sutherland theory of outer gap pulsar emission (Cheng and Ruderman 1977, 1980) which is related to the binding energy of ions in the stellar crust: $\varepsilon \lesssim 0.1$. The other objects which show X-ray sources with similar luminosities within the combined X-ray and radio error boxes are PSR 0355+54, PSR 1700-18, PSR 1702-18, and PSR 0031-07, although, for the latter source, a value of $\eta \gtrsim 100\%$ suggests that the positional coincidence with the pulsar may be serendipitous. Detailed analysis of these sources will be published elsewhere (Helfand and Chanan 1980).

By far the strongest X-ray source identified with a radio pulsar is PSR 1055-52. The offset between the radio position (Manchester, private communication) and the X-ray centroid as measured with the HRI is 3"±5". There are no stars in the X-ray error circle to the plate limit of the POSS ($\sim$ 20 magnitude) implying an X-ray-to-optical-luminosity ratio for the source of > 400. This is greater than that for any known class of X-ray-emitting objects with the sole exception of the accreting X-ray binary sources. However, the typical X-ray luminosity of such systems ranges from 10^{36} to 10^{38} erg s^{-1} implying a distance for this source of between 10 kpc (z = 1500 pc) and 100 kpc, far outside the galactic disk. Further arguments against the identification of the source with such a system is its extremely soft spectrum ($kT \lesssim 0.1$ keV as compared to typical binary system temperatures of $kT \gtrsim 10$ keV) and the lack of any strong interstellar cutoff at low energies ($n_H \lesssim 10^{22}$) which will be expected for such a distant source.

These spectral parameters are, however, consistent with what is expected from a hot neutron star at a distance of $\sim$ 1 kpc. Assuming a neutron star radius of 16 km, a distance of 1100 pc (Taylor and Manchester 1975) and an interstellar hydrogen density of 0.3 cm^{-3}, the observed IPC counting rate implies a blackbody temperature of $\sim 1 \times 10^6$ K. The HRI, with its different spectral response function, yields an independent spectral point which is also consistent with these parameters. In principle, the IPC data contain sufficient energy information to actually fit for the blackbody temperature of the source; coupled with the total flux, this would yield the first direct measurement of a neutron star radius. Residual calibration uncertainties in the spectral response function of the IPC have, to date, prevented us from performing such a detailed spectral fit, although recent progress in understanding the instrument response coupled with extensive inflight calibrations may soon make this possible. Preliminary one-temperature blackbody fits suggest a slightly lower value than that derived from the broadband photometry, implying that a somewhat larger radius may be required.

An important constraint on the emission from PSR 1055-52 is that, to the $\sim$ 15% level, the X-rays are not pulsed at the radio pulsar period. If the emission were dominated by hot polar caps, one would expect to see a large modulation of the signal in phase with the radio pulse peaks. Even for a more or less uniformly heated star, the large variations in thermal conductivity over the surface due to the changing radial component of the star's magnetic field might well be expected to produce a modulation. Under the assumption that, irrespective of the heating mechanism, the magnetic polar caps will be at a different temperature than the rest of the star, we can use the modulation limit to set a limit on the angle θ between the magnetic and rotation axes: $\theta \lesssim 20^o$ (see Helfand, Chanan, and Greenstein 1980 for a detailed discussion of this source). This pulsar has a strong radio interpulse (McCulloch et al. 1976), suggesting, in the two-pole model of interpulses, that the rotation and magnetic axes are nearly orthogonal. However, in the geometrical pulsar emission model of Radhakrishnan and Cooke (1969), the swing of the polarization position angle through the main pulse is consistent with a value for θ of $< 20^o$ and definitely inconsistent with $\theta = 90^o$. The X-ray data may, then, prove useful in settling the one-pole versus two-pole question of radio interpulse emission.

The X-ray luminosity of PSR 1055-52 ($L_x \approx 4 \times 10^{33}$ erg s^{-1}) is greater than that of the presumably younger Vela pulsar and far in excess of that observed for any other source with the sole exception of the Crab. The value of $\eta \approx 10\%$ implies an extremely efficient mechanism for converting rotational to thermal energy if the pulsar spin down is the sole source of energy input. In general, the distribution of detections and upper limits for the 18 sources studied shows an extremely large range in both L_x (or T) and η. Luminosities exhibit a spread of $> 10^3$; even for sources with similar periods such as PSR 1055-52, PSR 0655+64, and PSR 1929+10, the range is more than a factor of 300. It is clear that the variation in the flux observed for these sources is not simply a matter of seeing the largest or nearest of a set of objects with similar temperatures. Likewise, the spread of nearly five orders of magnitude in the values of η requires a large dynamic range for the process or processes which produce the thermal energy observed.

Why do we see no X-ray evidence of pulsars in the vast majority of supernova remnants we examine? Why is there such a large apparent range of temperatures among older radio pulsars and what mechanisms could be responsible for maintaining some stars at several hundred thousand degrees for $> 10^6$ yr? It appears, as the first results come in, that the opening of this new spectral window for pulsar research has served chiefly to augment our vast communal ignorance on the subject. But, as the recently improved cooling calculations suggest, significant new constraints will arise from these data as we continue in our attempt to understand the emission mechanism, structure, and evolution of radio pulsars.

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DISCUSSION

VAN DEN HEUVEL: Is it not a bit dangerous to express the X-ray flux in terms of the rotational energy loss, since the two might perhaps have no relation to one another (i.e. if the X-rays are simply due to loss of the heat left in the neutron star from its birth)?

HELFAND: Indeed, and some energy source other than the pulsar's spin-down may be the explanation for the wide range of values observed.