9 August 1974, Volume 185, Number 4150 **SCIENCE**

Prospects for Detecting Blackbody X-rays from Neutron Stars

George Greenstein and Jeffrey E. McClintock

Before the discovery of pulsars it was argued that neutron stars, if they existed, might be hot enough to emit detectable quantities of blackbody x-radiation: the way to prove that neutron stars did exist was then to find such x-ray sources. But the search was unsuccessful and none were ever found. With the discovery of pulsars and their identification with rotating neutron stars the motivation for this search lost its urgency and the idea seems to have died of neglect. We believe it should be resurrected.

It should be resurrected because we have never seen a neutron star. It must be emphasized that when observing pulsar radiation we are seeing, not a neutron star, but its magnetosphere. The two have almost no relation to each other, and, with one or perhaps two exceptions [pulsar timing irregularities and possibly the phenomenon of drifting subpulses (*1*)], pulsar radiation tells us virtually nothing about the internal structure of neutron stars. If this were not the case it would not have taken so long to decide that pulsars are neutron stars. As an analogy, pulsar radiation bears somewhat the same relation to neutron stars that solar flares do to the sun. Similarly, blackbody x-radiation from neutron stars bears the same relation to them that continuum starlight does to stars. And where would astronomy be without starlight?

One might argue that an understanding of neutron star structure can be achieved by theoreticians working in the absence of observational data. Perhaps it can. On the other hand, one is allowed to consider the solar neutrino experiment in this regard—or the fact that, using pure thought, Aristotle was able to demonstrate that the universe was finite, spherical, eternal, and perfect, and that the earth was at its center. Neutron stars are extreme and, what is more to the point, unfamiliar in almost every respect. A correct description of their structure is necessarily going to involve advances in a variety of fields lying on the frontiers of physics. Perhaps it is inevitable that some of our ideas concerning them are seriously in error. If so, only observations can set us right.

If we do detect and carefully measure blackbody x-ray spectra from neutron stars we will be able to learn a number of things:

1) The spectrum of this radiation determines the surface temperature of the star. The flux then determines its radius (if its distance is known). If this radius lies between about 10 and 100 kilometers we will have found strong evidence that pulsars really are neutron stars. If it does not, then we will have a fruitful contradiction.

2) If we believe our models, the derived stellar radius determines the stellar mass. Fruitful comparisons then become possible between, among other things, rotational energy loss rates and energy balances of supernova remnants.

3) The pulsar magnetic field, B, can now be determined, at least to order of magnitude, by the formula (*2*)

$$P\dot{P} = \frac{4\pi^2}{c^3} B^2 \frac{R^6}{I}$$

where R is the radius of the star, I its moment of inertia, and P its period of rotation; c is the speed of light; and $\dot{P}$ is the time derivative of P.

4) One can predict (*3–6*) the temperature of a neutron star if its age, mass, and magnetic field are known. If $P/\dot{P}$, the characteristic age of a pulsar, is a good indicator of its true age, then tests of these predictions are possible. Alternatively, one can use them to see if $P/\dot{P}$ is in fact a good age indicator.

5) The mass, magnetic field, and surface temperature of a neutron star theoretically determine its internal temperature. There is an indirect way to measure this internal temperature and so test the theory. The relaxation processes describing the coupling between charges and the neutron superfluid within the star depend on the star's temperature. These relaxation processes in turn determine the time constant of the quasi-exponential period decay one expects immediately following a period jump. At the time of this writing two pulsars, the Crab and Vela, have been observed to undergo period jumps followed by just such quasi-exponential period decays. The parameters of these decays have been roughly measured. And so, by following two completely different lines of argument —x-ray astronomy on the one hand and pulsar timing observations on the other, both combined with a good deal of theory—we have two potential methods for determining the temperatures of the Crab and Vela pulsars. It may not be inconceivable that these two determinations of their temperatures will agree.

How Hot Are They? (Theory)

In what follows we will consider three ways to answer this question.

Method 1: Cooling theory. When formed, a neutron star should be exceedingly hot. It cools with the passage of time. A zero-order calculation of

Dr. Greenstein is assistant professor of astronomy at Amherst College, Amherst, Massachusetts 01002. Dr. McClintock is staff scientist at the Center for Space Research, Massachusetts Institute of Technology, Cambridge 02139.

the cooling process yields ambiguous results: neutron stars corresponding to most known pulsars might be detectable as x-ray sources (if $P/\dot{P}$ is a good age indicator). One then tries to do the calculation better. But with the passage of time various monkey wrenches (neutrino emission, crystallization, superfluidity, pion condensation, and so forth) keep being thrown into the works. So the calculations keep being redone. Here we will adopt the most recent published computations (*3*), knowing full well that the precise numbers we quote are subject to change.

Method 2: Energy dissipation within the star. A neutron star is an end point of stellar evolution and, as such, is generally thought to possess no internal sources of energy. In fact this is not so. (i) If it possesses a solid crust (or core) and is precessing, a finite fraction of its rotational energy will be dissipated as heat within the solid (*4*). (ii) If it is superfluid and its rotation rate is slowing down, a finite fraction of its rotational energy will be frictionally dissipated as heat within the superfluid (*5, 6*). The theories of both these processes are in crude shape, and we do not yet know if either of them will turn out to be important. For the sake of argument we will adopt estimates based on process (ii), knowing full well that these too are subject to change. Within this theory the predicted temperature is relatively insensitive to the mass of the star and is given by

$$T = \frac{4 \times 10^7}{(Pt_y^2)^{1/6}} \, {}^\circ\mathrm{K}$$

where P is the period in seconds and $t_y = P/\dot{P}$ in years.

Method 3: Maximum possible energy dissipation. Because the theoretical situation regarding energy dissipation within neutron stars is so foggy, we also present an exact upper limit to the temperature that could be so maintained. This is the temperature that would be obtained if half the rotational energy of the star were dissipated internally as heat, the remainder being radiated away nonthermally (as magnetic dipole radiation, relativistic particles, or whatever). Within the framework of process (ii) this corresponds to the superfluid rotating significantly more rapidly than the crust. We then simply set $4\pi R^2 \sigma T^4$ (where R is the stellar radius and σ is the Stefan-Boltzmann constant) equal to $I\Omega\dot{\Omega}$ (where I is the stellar moment of inertia and Ω the stellar angular velocity). This method neglects neutrino radiation, which ought to be all right for all but the hottest of stars [if we neglect pion condensation (*7*)]. With the exception of this one caveat the numbers we adopt in this fashion are not subject to change. Of course, they may be meaningless.

How Hot Are They? (Observation)

At present there is no observational evidence whatsoever for the existence of thermal emission from the surface of a neutron star.

X-radiation has been detected from the Crab and Vela pulsars; however, the observed spectra are not blackbody (*8*). Although thermal x-radiation might be present in the fluxes from these objects, it will be difficult to separate the thermal contribution from the dominant contributions due to the pulsar mechanism and to the surrounding nebulas. We will return to this problem later.

Table 1. Upper limits on the temperatures of nearby pulsars based on results given in the 3U x-ray source catalog (*17*). Distances are from Ter Haar (*19*). The upper limit on blackbody temperature was calculated assuming $R = 10$ km; luminosity $= 4\pi R^2\sigma T^4$.

Pulsar	Distance (pc)	Upper limit on: Blackbody temperature kT (ev)	Blackbody temperature T (10^6 °K)	Luminosity (10^{34} erg/sec)
0328	500	260	3.0	5.8
0628	200	210	2.4	2.4
0736	400	240	2.8	4.4
0808	130	200	2.3	1.7
0834	400	240	2.8	4.4
0835	400	240	2.8	4.4
0940	500	260	3.0	5.8
0950	60	170	2.0	1.1
1133	130	200	2.3	1.7
1359	500	260	3.0	5.8
1451	250	220	2.5	2.8
1530	400	240	2.8	4.4
1604	250	220	2.5	2.8
1642	160	200	2.3	1.7
1706	200	210	2.4	2.4
1919	250	220	2.5	2.8
1929	70	180	2.1	1.4
1953	350	240	2.8	4.4
2016	300	230	2.7	3.8
2021	400	240	2.8	4.4
2045	400	240	2.8	4.4

Binary x-ray sources such as Hercules X-1 and Centaurus X-3 are widely believed to contain neutron stars, although a number of people are in strong disagreement with this hypothesis (*9*). Even if one accepts the existence of a neutron star in such a system, it is highly unlikely that thermal x-rays from its surface could be distinguished from the x-rays due to other poorly understood processes such as emission from matter accreting at the magnetic polar caps of the star (*10*) or from hot gas contained in a surrounding disk or halo (*11*).

Even less is known about x-ray sources which are not proved members of binary systems. It was strongly conjectured by Margon *et al.* (*12*) that one such object, GX 340 + 0, is a neutron star radiating at a blackbody temperature of 15×10^6 °K. This conclusion, which was based on spectral shape, is not widely accepted at present.

Gursky (*13*) and Bahcall and Yahill (*14*), for example, have discussed the suggestion of Margon *et al.* and some of the difficulties which arise in attempting to uniquely define a spectral shape on the basis of a chi-square analysis. Future observations with crystal spectrometers will allow us to reach a firmer conclusion about the nature of the observed turnover in the spectrum of GX 340 + 0 below 3 kev. The fraction of this turnover which is attributable to absorption by the interstellar-medium and by material around the source can be determined by measuring the strength of the photoelectric absorption edges (*15*), while the fraction of the spectrum which is genuinely blackbody will not show these features. Unfortunately, the first x-ray observatory that will be capable of clearly distinguishing an absorption cutoff from a blackbody cutoff—High Energy Astrophysics Observatory (HEAO) B of the Naval Research Laboratory—is presently scheduled for a 1978 launch.

We turn now to what we consider good potential candidates for detectable blackbody emission from neutron stars—the middle-aged pulsars. At some age, perhaps on the order of 100,000 years, it seems that the pulsar emission mechanism can no longer generate significant amounts of x-radiation, and by this time neither can the surrounding nebula. At that age, if the neutron star has remained sufficiently hot,

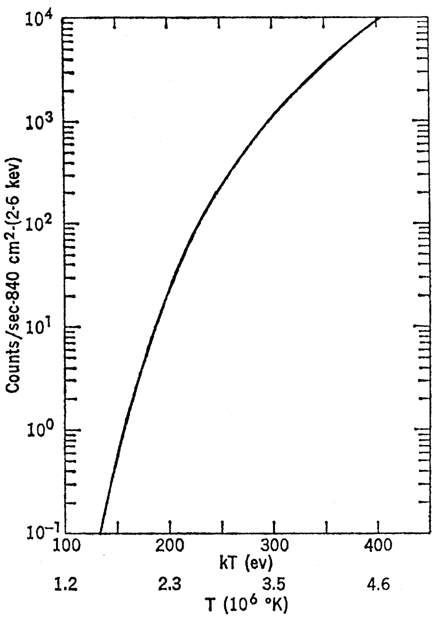

Fig. 1. Predicted counting rate in the Uhuru x-ray detectors as a function of the temperature of a blackbody with a radius of 10 km at a distance of 100 pc.

thermal x-radiation may be detectable.

With the exceptions of the Crab and Vela pulsars, none of the 60 pulsars listed by Manchester and Taylor (*16*) are identifiable with any of the 161 x-ray source positions given in the 3U x-ray source catalog (*17, 18*). This catalog was compiled from the results of nearly complete sky coverage by the Uhuru x-ray observatory to a sensitivity of approximately ten counts per second in the energy interval 2 to 6 kev. This result enables us to place upper limits on the temperatures of many pulsars. The blackbody photon flux at energy E(kev) from a neutron star of temperature kT(kev) is

$$N(E) = 1000(R/D)^2 \frac{E^2}{\exp(E/kT) - 1}$$

photon kev^{-1} cm^{-2} sec^{-1}

where R is the radius in units of 10 km and D is the distance in units of 100 parsecs (pc). Neglecting absorption by the interstellar medium ($\leqq 10$ percent for a distance of 1 kpc at energies above 2 kev), approximating the efficiency $\epsilon(E)$ of the Uhuru detectors by considering only the transmission efficiency of 0.002-inch (0.05-mm) beryllium foil, and neglecting the effects of detector energy resolution, one obtains a predicted counting rate

$$(840 \text{ cm}^2) \int_{2 \text{ kev}}^{6 \text{ kev}} N(E)\, \epsilon(E)\, dE \text{ count sec}^{-1}$$

The calculated counting rates are presented in Fig. 1 as a function of the blackbody temperature, T. Upper limits on the temperatures of 21 pulsars are then presented in Table 1. They were obtained by using the results shown in Fig. 1 and pulsar distance estimates due to Prentice (*19*).

We can estimate the expected temperature of a pulsar, using any of the three methods described above, once we know $\dot{P}$. A comparison between our expectations and the observed upper limits for a representative sample of pulsars is given in Table 2.

A first glance at Table 2 may well create a sense of despondency. The expected temperatures lie well below the observed upper limits—by factors generally greater than 10. Only the "extreme" method 3 predicts temperatures comparable, in a few cases, with the upper limits. The Uhuru observations are therefore telling us nothing too surprising. Of course, there are a number of ways in which one can do better. One obvious way is to increase the source observation time. For example, the Uhuru x-ray detectors are easily capable of achieving a much greater sensitivity on selected sources than ten counts per second (2 to 6 kev). However, a sensitivity 10 or even 100 times greater corresponds to a small decrease in the upper limit on the temperature of neutron star (see Fig. 1).

For a blackbody spectrum, the maximum photon flux is at an energy E_{max} (kev) $= 0.14T(10^6\ °K)$, and therefore a second way to do better is to extend one's detector response to lower energies. Unfortunately, photoelectric absorption by the interstellar medium becomes an important effect at energies below 1 kev. The photon mean free path is only about 100 pc at ¼ kev, the energy at which proportional counter detectors with polycarbonate windows are very efficient (the windows are relatively opaque between ¼ kev and ½ kev). Also large uncertainties in the final results are introduced by uncertainties in the composition and density of the interstellar medium (*15*). Nevertheless, detectors operating below 1 kev are the most sensitive thermometers we have for the nearest pulsars. A proportional counter detector system with a polypropylene window viewed PSR 1929 during a rocket flight conducted by a Massachusetts Institute of Technology group

Table 2. Comparison between observed upper limits and expected temperatures of middle-aged pulsars. The upper limits were derived from observations by the Uhuru satellite (see text). In method 1 we have taken the age of the star to be $\frac{1}{2}P/\dot{P}$ (P = period). The values are log [T(°K)]; their ranges reflect the dependence of temperature on the assumed mass of the star. Obs., observed.

Pulsar	Obs. upper limit (log T)	Expected temperatures (log T) Method 1	Method 2	Method 3
0950	6.3	2.4–3.1	5.1	5.0–6.0
1642	6.4	2.9–5.2	5.4	5.1–6.1
1706	6.4	3.1–5.2	5.4	5.1–6.1
1929	6.3	2.9–5.2	5.4	5.3–6.2
2016	6.4	<3.0	4.9	4.7–5.7
2021	6.4	2.9–5.2	5.4	4.5–5.5

on 19 May 1972 (*20*). The product of the peak efficiency and area of the detection system was 280 cm^2 at 0.28 kev. The effective source observation time was only ⅓ second: nevertheless, using the data from the article of Borken *et al.* (*20*), we deduce for PSR 1929

$$T < 7 \times 10^5\ °K$$
$$(\log T < 5.8)$$
$$\text{Luminosity} < 2 \times 10^{32} \text{ erg/sec}$$
$$(R = 10 \text{ km})$$
$$(D = 70 \text{ pc})$$

This limit is interesting, for it lies well below the prediction of method 3 for high mass stars. Therefore, if PSR 1929 converts a significant fraction of its rotational energy to heat in any way whatsoever, it cannot be of the very highest mass.

The limits given above and in Table 1 assume a stellar radius of 10 km. Neutron stars of the very lowest mass have radii 10 times this value, and therefore at the same temperature the predicted counting rate would be 100 times greater. From Fig. 1 we see that the upper limit on the temperature is then reduced by less than a factor of 2.

What Is To Be Done? (*21*)

As shown in Fig. 1, a slight increase in temperature yields an enormous increase in detectability. This makes recently formed neutron stars, the Crab and Vela pulsars for example, good potential candidates. Unfortunately, the x-rays emitted by the surrounding nebulas and produced by the pulsar mechanism itself make it difficult to observe thermal x-rays from these objects. There are at least three supernova remnants—Cassiopeia A (Cas A), Tycho, and Kepler—which are even younger than the Crab and Vela remnants. They are 300 to 400 years of age. As yet, no pulsar has been detected in any of them. X-radiation has been detected from Cas A and Tycho, but not from Kepler. The spectra and intensities of Cas A and Tycho have been measured by Gorenstein *et al.* (*22*). The luminosity of Cas A is 5×10^{36} erg/sec (distance = 3.4 kpc) and the luminosity of Tycho is approximately a factor of 3 less (distance = 3.5 kpc). A recent observation of Cas A by Fabian *et al.* (*23*) indicates that the bulk of the radiation does not come from a compact object. Much work will be needed on these and other supernova remnants (for example, Puppis A, the Cygnus Loop, IC443, and MSH15-52A) to determine whether or not they contain hot neutron stars. In this context, we note that an x-ray "hot spot" was recently discovered in the center of the Cygnus Loop (*24*).

Of course, not all supernovas need form neutron stars. The youngest supernova remnant that we know to contain one is the Crab. Predicted surface temperatures for this object lie in the range 5×10^5 °K to 2×10^7 °K. At less than 10^6 °K thermal emission from the neutron star would be swamped by nonthermal emission from the nebula, making the star very difficult to detect. Conversely, at 2×10^7 °K thermal emission from the star would be several times the nebular emission. We can place a rough limit of 5×10^6 °K on the Crab pulsar's temperature by noting that, were the temperature much higher, the 1964 lunar occultation experiment of the Naval Research Laboratory (NRL) group (*25*) would have detected it (*6*). In fact, just such a lunar occultation method as the NRL group employed would seem to be the only way to detect thermal radiation from the Crab pulsar. Greenstein (*6*) has described a possible observation and noted that a series of 20 lunar occultations of the Crab will commence in the spring of 1974.

Because the Crab Nebula almost certainly contains a neutron star, because this star almost certainly is hotter than any other (with the possible exceptions of neutron stars in younger supernova remnants which contain no observed pulsars), because detectability is such a strong function of temperature, and because lunar occultations probably provide our only means of separating emission from the star from that due to the nebula—for all these reasons we strongly feel that these occultations should be exploited to their fullest.

Returning to the older pulsars, the best limit we have at present on the temperature of a pulsar is that for PSR 1929 ($\log T < 5.8$). The limit is good simply because the pulsar is sufficiently close that low-energy photons (<1 kev) are not absorbed by the interstellar medium. It seems worthwhile, therefore, to direct attention to low-energy studies (<1 kev) of the closest middle-aged pulsars. The HEAO-B x-ray observatory, presently scheduled for a 1978 launch, is expected to be able to reach a sensitivity of 3×10^{-16} erg cm^{-2} sec^{-1} in the energy interval 0.1 to 0.28 kev in 10^5 seconds of observation (*26*). Failure to observe PSR 1929 at this sensitivity will reduce the limiting temperature of the pulsar to 2×10^5 °K ($\log T < 5.3$).

Observations of more distant pulsars (at distances greater than 300 pc) are severely limited by interstellar absorption at energies below 1 kev. It is therefore unlikely that limits on their temperatures can ever be pushed significantly below 10^6 °K.

References and Notes

1. G. Huguenin, R. Manchester, J. Taylor, *Astrophys. J.* **169**, 97 (1971).

P. Goldreich and W. Julian, *ibid.* **157**, 869 (19[illegible] J. Ostriker and J. Gunn, *ibid.*, p. 1395.

3. S. Tsuruta, V. Canuto, J. Lodenquai, M. Ruderman, *ibid.* **176**, 739 (1972) and references cited therein.
4. R. Henriksen, P. Feldman, W. Chau, *ibid.* **172**, 717 (1972).
5. G. Greenstein, *Nat. Phys. Sci.* **232**, 117 (1971); *ibid.* **238**, 71 (1972); *Nature (Lond.)* **234**, 180 (1971).
6. ———, *Physics Dense Matter, Proc. IAU (Int. Astron. Union) Symp. No. 53*, in press.
7. R. Sawyer, *Phys. Rev. Lett.* **29**, 382 (1972); D. Scalapino, *ibid.*, p. 386; J. Kogut and J. Manassah, *Phys. Lett. A* **41**, 129 (1972).
8. J. D. Kurfess, *Astrophys. J. Lett.* **168**, L39 (1971); E. Kellogg, H. Tananbaum, F. R. Harnden, Jr., H. Gursky, R. Giacconi, *Astrophys. J.* **183**, 935 (1973).
9. A. Prakash, in *Proceedings of the Sixth Texas Symposium on Relativistic Astrophysics*, New York, December 1972 (New York Academy of Sciences, New York, in press); K. Brecher and P. Morrison, *Astrophys. J. Lett.* **180**, L107 (1973).
10. F. K. Lamb, C. J. Pethick, D. Pines, *Astrophys. J.* **184**, 271 (1973).
11. J. E. Pringle and M. J. Rees, *Astron. Astrophys.* **21**, 1 (1972).
12. B. Margon, S. Bowyer, L. Michael, R. Cruddace, *Astrophys. J. Lett.* **169**, L45 (1971).
13. H. Gursky, lectures presented at the Summer School of Theoretical Physics, Les Hoches, France, August 1972.
14. J. N. Bahcall and A. Yahill, *Nat. Phys. Sci.* **238**, 92 (1972).
15. R. L. Brown and R. J. Gould, *Phys. Rev. D* **1**, 2252 (1970).
16. R. N. Manchester and J. H. Taylor, *Astrophys. Lett.* **10**, 67 (1972).
17. R. Giacconi, S. Murray, H. Gursky, E. Kellogg, E. Schreier, T. Matilsky, D. Koch, H. Tananbaum, *Astrophys. J. Suppl.* **27** (No. 237) (1974).
18. As noted in the 3U catalog (*17*), PSR0611 + 22 is within the error box of the weak x-ray source 3U0620 + 23. Because this error box is large—6 square degrees—we regard this coincidence as fortuitous.
19. A. J. R. Prentice, cited in D. Ter Haar, *Phys. Rep. (Phys. Lett. C)* **3** (No 2), 57 (1972).
20. R. Borken, R. Doxsey, S. Rappaport, *Astrophys. J. Lett.* **178**, L115 (1972).
21. V. I. Lenin, *What Is To Be Done?* (International Publishers, New York, 1929); N. G. Chernyshevskii, *What Is To Be Done?* (Vintage, New York, 1961).
22. P. Gorenstein, E. M. Kellogg, H. Gursky, *Astrophys. J.* **160**, 199 (1970).
23. A. C. Fabian, J. C. Zarnecki, J. L. Culhane, *Nat. Phys. Sci.* **242**, 18 (1973).
24. S. Rappaport, W. Cash, R. Doxsey, G. Moore, *IAU (Int. Astron. Union) Circ. No. 2553* (1973); J. C. Stevens and G. Garmire, *Astrophys. J. Lett.* **180**, L19 (1973).
25. S. Bowyer, E. T. Byram, T. A. Chubb, H. Friedman, *Science* **146**, 912 (1964).
26. P. Gorenstein, private communication.

27. We are grateful to the Bell Telephone System for making this collaboration possible. This research was supported in part by NSF grant GP 31410. Contribution No. 169 of the Five College Observatory.