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RADIUS OF THE VELA PULSAR*

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ABSTRACT

Lasker has proposed to identify a $B \approx 23.7$ mag star as thermal radiation from the hot neutron star associated with the Vela pulsar. We show that this identification, if correct, together with existing X-ray surveys of the Vela supernova remnant, requires that the radius of this pulsar certainly exceed 45 km, and probably 95 km.

Subject headings: pulsars — stars: neutron

I. LIMITS ON THE RADIUS OF THE VELA PULSAR

Lasker (1976) has proposed to identify a $B \approx 23.7$ mag object as thermal radiation from the surface of the hot neutron star associated with the Vela pulsar. The colors of the candidate star and its agreement in position with that of the pulsar are striking. Here we show that this identification, if correct, together with existing X-ray surveys of the Vela supernova remnant, places severe limits on this pulsar's radius.

An object of radius R (km), temperature T (K) at a distance D (kpc) has magnitude

$$m_{\rm vis} = 50.2 - 5 \log R + 5 \log D - 2.5 \log T\,. \quad (1)$$

Specializing to $B \approx 23.7$ ($m_{\rm vis} \approx 24.2$) and choosing the distance to the Vela pulsar to be 500 pc (Taylor and Manchester 1975) this relation yields the temperature of the pulsar given its radius. For instance, the canonical choice $R = 10$ km yields $T \approx 5 \times 10^7$ K.

Such a high temperature can be immediately ruled out. The X-ray spectrum of the Vela supernova remnant in the 2–10 keV region can be described by a power law of the form (Kellogg *et al.* 1973)

$$F(E) = (5.6 \pm 1.0) 10^{-11} E^{-(1.1\pm0.3)} \times \text{ergs cm}^{-2}\,\text{s}^{-1}\,\text{keV}^{-1} \quad (2)$$

(E = energy in keV). A blackbody of radius 10 km, temperature 5×10^7 K, at a distance of 500 pc produces a flux in the 2–10 keV band some six orders of magnitude greater than this.

The difficulty can be resolved by going to larger radii. As the assumed radius of the Vela pulsar is increased, the temperature derived from equation (1) and the predicted blackbody flux in the X-ray region both drop. The blackbody flux becomes less than the observed flux for radii greater than 70 km (at a distance of 500 pc).

With a little more work we can derive more stringent limits from a low-energy survey of the Vela supernova remnant conducted by Moore and Garmire (1975). The pulsar is located in cell number 77 of their Table 2, which shows no emission to within 1 standard error. We have, then, the observed limits ($2\,\sigma$) on the low-energy X-ray flux from the Vela pulsar listed in column (2) of Table 1. The flux from a hot neutron star is just the integral of the Planck function times $\exp(-\tau)$ (τ is the optical depth) over each energy band divided by the bandwidth. We find lower bounds on the radius of the Vela pulsar by requiring that these fluxes not exceed the observed limits on the flux. In doing these integrals we have used the interstellar absorption cross sections of Brown and Gould (1970). We also need to know the hydrogen column density $N_{\rm H}$ and the distance to the pulsar.

PSR 0833 is clearly associated with the Vela X supernova remnant (Kristian 1970). Several different determinations of the distance to the remnant and to PSR 0833 are consistent with the value 500 pc. We believe this number to be accurate to within 30 percent. Reviews of the distance determinations are given by Brandt *et al.* (1971) and Kristian (1970).

Soft X-ray studies indicate that the hydrogen column densities in the directions of Vela XRS-1 and Vela XRS-2 are $\sim 1.5 \times 10^{20}$ and 3×10^{20} cm^{-2}, respectively (Gorenstein *et al.* 1974; Moore and Garmire 1975). We adopt the more conservative value, 3×10^{20} cm^{-2}, that is, the value that leads to a smaller limit on the radius. (We consider it likely that $N_{\rm H}$ lies between 1.5×10^{20} and 10^{21} cm^{-2}.)

The resulting limits on the radius of the Vela pulsar are given in the remaining columns of Table 1. None approaches the canonical choice $R = 10$ km. The limit derived from the 1–2 keV data is unaffected by the relatively difficult question of the hydrogen column density in the direction of the pulsar. The weakest limit derived from these data is $R > 45$ km ($D = 350$ pc). A comparable limit with this choice for the distance

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TABLE 1

LOWER LIMITS TO THE RADIUS OF THE VELA PULSAR

Band (keV)	Limiting Flux* (photons cm^{-2} s^{-1} keV^{-1})	Limiting Radius (km)				
		$D = 500$ pc, $N_H = 1.5 \times 10^{20}$cm^{-2}	$D = 500$ pc, $N_H = 3 \times 10^{20}$cm^{-2}	$D = 500$ pc, $N_H = 10^{21}$cm^{-2}	$D = 350$ pc, $N_H = 3 \times 10^{20}$cm^{-2}	$D = 600$ pc, $N_H = 3 \times 10^{20}$cm^{-2}
0.15–0.5..	0.7	105	95	85	65	115
0.5–1.0...	0.18	90	90	85	60	105
1.0–2.0...	0.1	65	65	65	45	80

* 2 σ limits.

follows from the 2–10 keV data. This limit is therefore quite reliable. The lowest-energy data yield far stronger limits, but they depend somewhat on one's choice for N_H. Our best guess ($N_H = 3 \times 10^{20}$ cm^{-2}, $D = 500$ pc) yields $R > 95$ km.

II. DISCUSSION

If Lasker's identification is correct, then a number of conclusions follow. For a neutron star, a large radius implies a low mass. There exist in the literature two lines of argument, one theoretical (Ruderman 1972) and the other observational (Greenstein 1972), that low-mass neutron stars simply do not exist. They will have to be rethought. A low-mass neutron star cannot possess a solid core, so the corequake theory of the Vela pulsar's period jumps (Pines, Shaham, and Ruderman 1972) will have to be abandoned. Many of the published neutron star models never allow the stellar radius to reach the very large values listed in Table 1; Lasker's identification has therefore placed severe constraints on the equation of state of dense matter. Finally—and we believe this point to be most important—this observation has made possible the first direct measurement of the dimensions of the object associated with the pulsar phenomenon. We find it comforting, to say the least, that this dimension turns out to be roughly comparable with that of a neutron star.

The consequences of Lasker's identification are therefore sufficiently important that serious attempts must be made to test it. One approach would be to understand the disagreements among the published radio positions of the Vela pulsar and also between the radio position and that of the optical source. Another would be to determine whether the optical spectrum truly is blackbody (using photon counting techniques): a determination of the spectrum would, of course, yield a value for the pulsar's radius rather than a limit. Still another approach would be to search for proper motion. It is quite clear by now that the pulsars are high-velocity objects: at a velocity of $\sim$200 km s^{-1} and a distance of $\sim$500 pc the proper motion would be of order 0".1 yr^{-1}. Finally, there are those who believe that the magnetic poles of a neutron star are hotter than its equator. If so, the candidate star should be fluctuating—with precisely the pulsar period,[1] but with low amplitude and wide duty cycle. The discovery of this phenomenon would, at the very least, confirm Lasker's identification. It could do more. If it could be shown that the peak of the optical light curve coincides in time with the arrival of a radio pulse (corrected for dispersion delay), one would have shown that pulsar radiation originates at the polar caps of a neutron star. Conversely, if the two do not coincide, one would have shown that this radiation originates somewhere out toward the speed-of-light cylinder.

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[1] Half the pulsar period in the unlikely event that the surface field is precisely that of a centered dipole oriented in such a way that we are equally illuminated by both poles.

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