Evidence for an X-ray Jet from the Vela Pulsar

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The Vela pulsar, PSR 0833–45, is one of the nearest active pulsars detected from radio to gamma-ray energies (1–5). The pulsar is embedded in a ~ 50 parsec diameter supernova remnant (6) of about the same age as the pulsar's spindown age $\sim 10^4$ yr (7), and is also surrounded by a much smaller, 0.5 pc compact X-ray nebula (8,9,10). Emission from the pulsar and its compact nebula account for less than a percent of the pulsar's rotational energy loss rate of 7×10^{36} erg s^{-1} . The specific manner in which the remaining luminosity is disposed of is still a mystery. Some current theories suggest that the balance of the power may be carried away by an equatorial wind of relativistic plasma (11). In this letter we report the discovery of a jet of X-ray emission, originating at the Vela pulsar and extending $\sim$7 pc toward the southwest along the pulsar spin axis (12), indicating a polar rather than an equatorial outflow. Furthermore, we show that the jet may be the previously undetected mechanism transporting almost all of the pulsar's rotational spindown power. One-sided jets, such as the one observed in Vela, may accelerate pulsars to large space velocities and offer an alternative to supernova kicks.

The Vela pulsar and its surrounding 1°-radius field was observed by the *Rosat* X-ray telescope with the Position Sensitive Proportional Counter (PSPC) at the focus during 1991 in two separate pointings: April 22.0–23.9 for 13900 sec and December 4.7–19.8 for 18500 sec. An image in the *Rosat* hard X-ray band (0.9–2.0 keV) of the combined pointings is shown in Figure 1 and reveals a remarkable jet of diffuse emission which originates at the pulsar and extends south-southwestward. This jet is $45'$ in length and $12'$ wide (FWHM), corresponding to 6.5 and 1.7 parsecs, respectively, at an assumed pulsar distance of 500 parsecs. The intensity profile across the jet feature appears to be gaussian and does not show any limb brightening. Diffuse X-ray emission has been detected previously from southwest of the pulsar (8) by *Einstein* , but this *Rosat* observation is the first to reveal that the feature is narrow, collimated, and remarkably symmetrical. We infer from the morphology of the feature and the fact that the pulsar lies at one end (at least in projection), that the feature is indeed a pulsar jet.

The spectrum of the jet was modeled as thermal plasma and power law emission. We have restricted our fits to the energy range 0.7–2.4 keV — the range where the jet is visible — and have fixed the value of the interstellar neutral hydrogen column density to be 2.6×10^{20} cm^{-2} (8). The nebular X-ray background and its fluctuations were estimated from the entire PSPC field of view, excluding the jet and pulsar neighborhood. Although the spectrum contains more than 85,000 counts, fluctuations of about 15% due to the patchiness of the background are the dominant source of error, and limit the accuracy of the spectral fits. The resulting best-fit parameters are shown in Table 1. The values of the χ^2 per d.o.f. were acceptable for both models. Outwards of $5'$ (*i.e.,* beyond the compact nebula) there are no significant spectral variations over the jet's length. The total emitted luminosity in the 0.7–2.4 keV bandpass, for either model, is approximately 10^{33} erg s^{-1} .

Even though both spectral models fit the data in the stated energy range, we prefer to adopt the thermal spectral model. A continuous power law emission model does not accurately reflect the data when extended to softer X-rays and even lower energies (13,14). It is conceivable that a more detailed model could be made consistent with the data, but it may be difficult to verify this hypothesis using *Rosat* because of its limited spectral resolution. In the rest of our discussion we assume that the X-rays observed from the jet are predominantly from hot thermal plasma emission with 1.3 keV temperature and 0.4 cm^{-3} density.

The physical parameters of the jet such as its speed, mass flow, and mechanical power can now be computed using existing models for extragalactic and protostellar jets (15–18). These models generally take the jet to be a beam of supersonic neutral material moving at speed v_j, which interacts with the ambient medium at a shock front often called a "working surface" or "head." For the case of the Vela jet, the average speed of the head, v_h, can be estimated directly, using the known pulsar age, to be at least 6.5 parsec$/11,000\,\mathrm{yr}\simeq 570$ km s^{-1} and larger if the jet is inclined to our line of sight. Uncertainties in the pulsar distance and age could influence this value by about a factor of 2. Behind the working surface, beam material which has been heated and deflected rearward by the shock zones will collect in a "cocoon" of hot gas (19). We propose that the observed X-rays are emission from the thermal plasma in the cocoon.

The speed of the jet can be estimated as follows, if we assume the head moves with a constant velocity. A jet beam of density ρ_j acting on a working surface of area A_j exerts a force $A_j\rho_j(v_j - v_h)^2$, which must be balanced by the force of the ambient material, $A_h\rho_a v_h^2$, of density ρ_a impinging on a bow shock whose area is A_h. This leads to a solution for the jet velocity, $v_j/v_h = 1 + \sqrt{A_h\rho_a/A_j\rho_j}$. The term $A_j\rho_j$ can be eliminated from the equation by considering that the cocoon density must be made of ambient and jet-added components, or $\rho_c = \rho_a + (v_j/v_h)(A_j\rho_j)/A_c$. These equations can be combined, assuming that the areas of the head and cocoon are approximately equal and using density values from Table 1, to give the jet speed $v_j = 1.8\ v_h \simeq 1100$ km s^{-1}. While this speed is non-relativistic, it is possible that the jet is ejected relativistically from the pulsar magnetosphere, but is slowed by entraining additional ambient material on its way to the working surface. $A_j\rho_j$ is 6×10^{12} gm cm^{-1}, the linear mass density in the jet. We estimate that these values are uncertain by a factor of 2–4.

The total mechanical power required to drive this jet is approximately the pulsar's rotational energy loss rate. The jet power is easily seen to be $\dot{E} = \frac{1}{2}\dot{M}_j v_j^2 = \frac{1}{2}A_j\rho_j v_j^3$. Using the solution above for $A_j\rho_j$ and v_j, the we find that the jet must be powered by 4×10^{36} erg s^{-1} , or almost 50% of the current pulsar spindown power! Although this value is an order of magnitude estimate, it is remarkable that a direct measurement of the head velocity and the plasma parameters of the jet combine to yield a mechanical luminosity which is close to the correct value; this is a powerful argument for the pulsar-jet association.

As measured from the X-rays, the cocoon density exceeds the ambient density by a factor of four. This implies that there is a mass flow in the jet, at a rate of $\dot{M}_j = A_j \rho_j v_j \sim 10^{-5} \mathrm{M}_\odot$ yr^{-1}. This is a huge mass flow which could not originate deep from within the pulsar magnetosphere, because it is energetically impossible to extract this much mass from a 1.4 $\mathrm{M}_\odot$ neutron star surface. The pulsar itself also could not have swept up this much mass via its northwesterly proper motion (13). We suggest that the excess mass must come from the ambient medium by entrainment through the cocoon. Considering that the jet axis is nearly perpendicular to the pulsar proper motion direction, it may indeed be sweeping up ambient material all along its length. In fact, the *Rosat* image reveals that the jet curves slightly southward, indicating that it may be interacting with the material and being swept backward.

Radio maps of the Vela region (20) at a frequency of 408 MHz show that the endpoint of the X-ray jet is coincident with Vela X, the brightest radio component of the supernova remnant, suggesting that electrons, shock-accelerated by the sudden jet termination, are cooling by radio synchrotron emission. This X-ray connection between the pulsar and Vela X was first noticed by Harnden *et al.* (8) in 1985, but at that time the cause of the X-rays was unclear since the pulsar's proper motion was not established. Radio polarization measurements of the same region (21) show that the projected magnetic fields are generally aligned along the X-ray jet, bringing the possibility that the cocoon, and perhaps the jet itself, are magnetically confined.

There are several interesting implications of pulsars with jets, beyond simple novelty. First, a jet provides a clear way for the pulsar to re-energize its supernova remnant over its lifetime, since it can deposit its total "birth" rotational energy, $E_{rot} \sim 10^{49} - 10^{51}$ erg, comparable to the total mechanical energy in a supernova explosion. Thus it may be possible for jets to alter the shape of supernova remnants over a long enough time period; Manchester (22) has pointed out that many supernova remnants appear to have a "biconical" configuration associated with a bipolar pulsar outflow.

A second consequence of pulsar jets is that asymmetric jets can accelerate the neutron star after the supernova explosion. Assuming no counterjet, the force on the Vela Pulsar is $A_j \rho_j v_j^2 \sim 8 \times 10^{28}$ dynes. Over the 10^4 year pulsar lifetime, this force could impart a velocity of 90 km s^{-1} which is comparable to the pulsar's current transverse proper motion of about 110 km s^{-1} (13). If similar conditions hold for the next 10^5 yr, Vela could be transformed from a slow to a fast moving pulsar. Although it does not appear that the jet is entirely responsible for Vela's present proper motion because the two axes are not aligned, jet acceleration does provide an intriguing alternative to the supernova explosion "kick" theories often invoked to explain proper motions. The remarkable fact that the observed mean pulsar velocity is 450 km s^{-1} (23) may be a consequence of post-supernova acceleration mechanisms such as one-sided jets, rather than a high-velocity birth distribution.

There remains the question of the one-sidedness of the Vela pulsar jet. Since relativistic effects are excluded for the velocities we derive, we can only suspect that either there must be asymmetries involved in the pulsar magnetic field making the jet one-sided; or alternatively, the effect of anisotropies in the circumpulsar material distribution may modify the counterjet beyond recognition.

We must stress that the jet model that we have constructed in this letter is not unique. For example, we have not pursued the synchrotron model in depth, as it did not seem consistent with observations at other wavelengths. Additionally, our thermal plasma spectral modelling has assumed a uniform density; the effects of clumping, for instance, would reduce average densities and introduce multitemperature components. These are configurations which cannot be distinguished by *Rosat* . We anticipate that future multiwavelength measurements, with improved instrumentation together with more sophisticated modelling, will really pin down the nature of the Vela jet.

1 References

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3 Tables

Table 1. Temperature, density and pressure of Vela's compact nebula (which dominates in the $2'$ –$5'$ region), the jet ($5'$ –$45'$), and the ambient supernova remnant. We assume that the depth of the jet in the line-of-sight is approximately 1 parsec for density calculations, and that the distance to the pulsar is 500 parsec in order to determine luminosity L_x. The parameter α is the index of the incident photon number spectrum. Formal statistical errors are approximately ±20% at a 2σ confidence level.

	Plasma			Power Law	
Distance arcmin	Temp keV	Density cm^{-3}	Pressure 10^{-8} erg cm^{-3}	L_x (0.7–2.4 keV) 10^{32} erg s^{-1}	α
2–5	6.7	1.2	2.5	0.9	1.7
5–45	1.3	0.4	0.19	7.0	3.1
ambient	0.12	0.11	0.004	—	—

4 Figure Captions

Figure 1. *Rosat* PSPC hard X-ray (0.9–2.0 keV) image of the Vela pulsar and a 1° radius field. The pulsar and its $1'$ radius compact nebula are at image center (indicated by a cross). The jet projects from the pulsar in the south-southwest direction (in this image north is up and east is left). We also note that a weaker region of diffuse emission is present, which connects the pulsar to its apparent birthplace about $8'$ to the southeast, as determined from its age and proper motion (13). The image has been corrected for telescope vignetting and is smoothed by a $45''$ radius gaussian filter. Intensity levels range from 0 (black) to 9×10^{-4} (white) counts per second per pixel of $15''$ square. The horizontal white bar is $10'$ long.