NEW VIEWS OF THE VELA PULSAR JET

C. B. MARKWARDT AND H. B. ÖGELMAN
University of Wisconsin — Madison
Department of Physics
1150 University Ave
Madison, WI 53706

Abstract. An X-ray jet-like outflow, beginning at the Vela pulsar and extending about seven parsecs along the pulsar spin axis direction has recently been discovered (Markwardt and Ögelman 1995). We present data obtained by the X-ray ASCA satellite which confirms the enhanced X-ray emission at the jet head and discuss the possible spectral models and physical interpretations. The jet parameters are updated according to the combined ROSAT and ASCA results.

1. Introduction

While isolated pulsars are known to be losing rotational energy over time, it is unclear precisely how this energy escapes from the pulsar, since direct radiation accounts for only a small fraction. Most theories hold that the balance of the power leaves the pulsar in the form of a coherent particle outflow. The emission from the Crab Nebula, for example, can be explained as synchrotron radiation from high-energy electrons which have been accelerated in a shocked outflow from the pulsar. The luminosity of the entire nebula is consistent with the spindown luminosity of the Crab pulsar. The Vela pulsar, PSR 0833–45, has a spindown age of $\tau \simeq 10^4$ yr, an estimated distance of 500 pc, and a rotational energy loss rate of 7×10^{36} erg s^{-1}(Taylor, Manchester & Lyne 1993). Recent X-ray observations by ROSAT (Markwardt & Ögelman 1995, hereafter MÖ), suggest that there is a polar outflow which forms a jet interacting with the supernova remnant (SNR; see Figure 1).

They interpret the observed X-ray structure to be thermal emission from a shock-heated cocoon of gas surrounding the jet itself. By estimating the density of the SNR interior and the cocoon structure, they were able

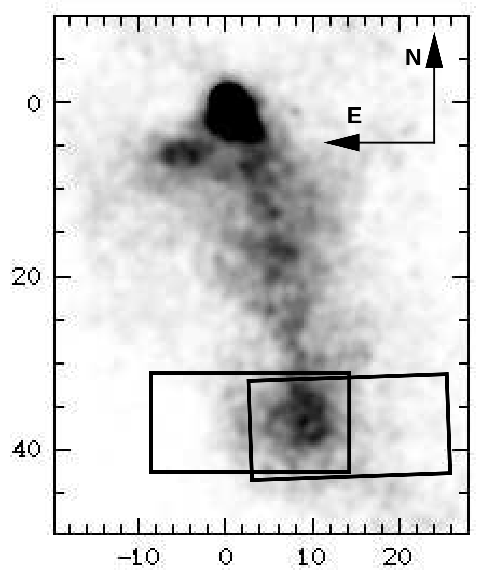

Figure 1. ROSAT X-ray (0.7–2.4 keV) image of the Vela pulsar jet. The rectangles indicate the ASCA SIS fields of view. The Vela pulsar is at coordinate (0,0), measured in arcminutes.

to demonstrate that the mechanical energy required to drive the jet into the SNR interior was comparable to the spindown luminosity of the Vela pulsar. Spatially, the jet is $45' \times 12'$ and centrally brightened, corresponding to 6.5 pc $\times$ 1.7 pc at a distance of 500 pc, and coincides roughly with the radio feature Vela X. MÖ determined that the cocoon spectrum is spatially uniform, described by a thermal plasma model with a temperature of 1.3 keV and density 0.4 cm^{-3}, apparent only above 0.7 keV. Below that energy, emission from the Vela SNR as a whole dominates the spectrum. The spectral fit to the ROSAT data is not unique however: a power-law is also satisfactory but over predicts the jet emission when extended to lower energy X-rays.

We present new observations by the ASCA X-ray telescope of the "head" of the cocoon, the point where the jet is believed to interact with the supernova remnant, and a revised interpretation of the cocoon kinematic model originally proposed by MÖ.

2. Spectral Observations

In order to gain insight on the emission mechanism of the jet we have performed additional observations of the head of the jet with the ASCA X-ray telescope. The ASCA SIS instrument is sensitive to higher energy

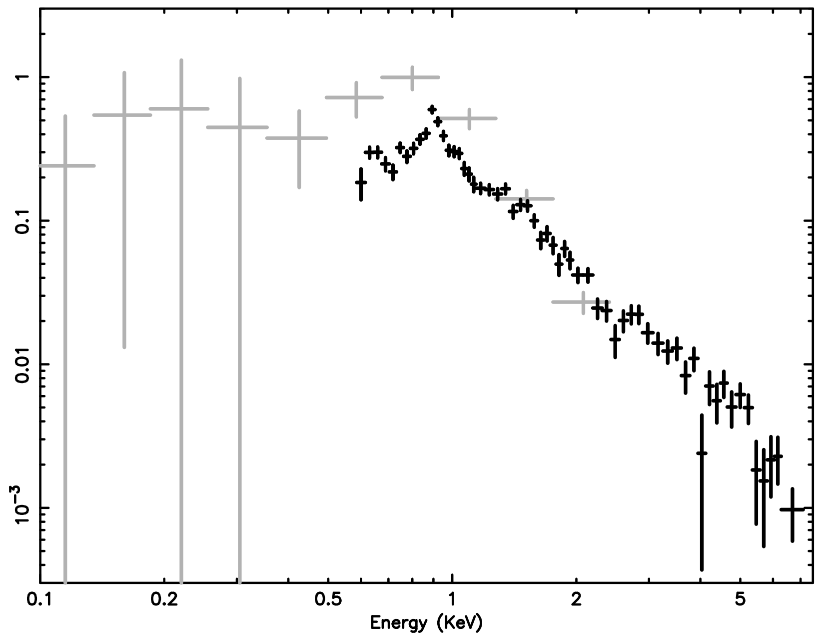

Figure 2. Combined ROSAT and ASCA spectrum of the Vela jet head in units of count s^{-1} keV^{-1} per unit CCD area of 11×11 $arcmin^2$. Gray points from 0.1–2.4 keV are ROSAT bins, while black points from 0.7–7.0 keV are ASCA bins. Below 0.7 keV background emission dominates and the cocoon spectrum is ill-determined.

X-rays than ROSAT, 0.5–10 keV, and has spectral resolution of $\sim 5\%$ at 1 keV, much better than ROSAT. Figure 1 shows the observed ASCA SIS fields of view superimposed on the ROSAT image. The observed ASCA X-ray enhancement of the jet is 2–3×10^{-3} ct s^{-1} $arcmin^{-2}$. The feature is centrally brightened with no evidence of limb-brightening, consistent with the ROSAT results.

The background-subtracted spectrum of the jet cocoon, combining both ROSAT and ASCA observations, is shown in Figure 2, and extends to energies of $\sim$7 keV (the sensitivity limit). The head spectrum is remarkably smooth except for the spectral peak near 0.9 keV, suggestive of Neon IX emission from gas below temperatures of 0.3 keV. The high energy portion of the spectrum however, demands temperatures of $\sim$4 keV if thermal. Because a single emission model is clearly not consistent with the data, two-component models consisting of a soft Raymond & Smith (1977) thermal component and a harder thermal/power-law component were fit to the combined ROSAT+ASCA spectrum and the results are shown in Table 1.

TABLE 1. Fitted jet and SNR head spectral parameters.

Soft Thermal + Hard Thermal

Comp.	Temp.(keV)	Frac.of flux	n_e (cm^{-3})
Soft	0.3	50%	0.41
Hard	3.7	50%	0.33
Soft Thermal + Hard Power Law			
Comp.	Temp.(keV)	Frac.of flux	n_e (cm^{-3})
Soft	0.3	35%	0.30
Hard	α=-2.1	65%	-

3. Cocoon Model

In the cocoon model, the pulsar produces a thin collimated outflow or jet beam, at a speed v_j, which interacts with the SNR at the working surface, traveling at a speed v_h. Shock heating at the working surface causes the gas to expand laterally into a cocoon of hot gas surrounding the jet beam (see Figure 3). A large fraction of the Vela pulsar spindown luminosity drives the outflow, which in turn goes into heating the gas and expanding the cocoon. The observed X-ray emission is thus from the hot cocoon plasma and not the jet itself.

The physical parameters of the cocoon model have not changed significantly after including the ASCA results. The average speed of the head, v_h, can be estimated directly as the cocoon length divided by the pulsar age to be $\simeq 570$ km s^{-1}, or larger if the jet is inclined to our line of sight. The speed of the jet, v_j 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 $\rho_c = \rho_a + (v_j/v_h)(A_j \rho_j)/A_c$. After combining the two equations and estimating the cocoon and SNR densities based on their emission measures (as listed in Table 1), we obtain

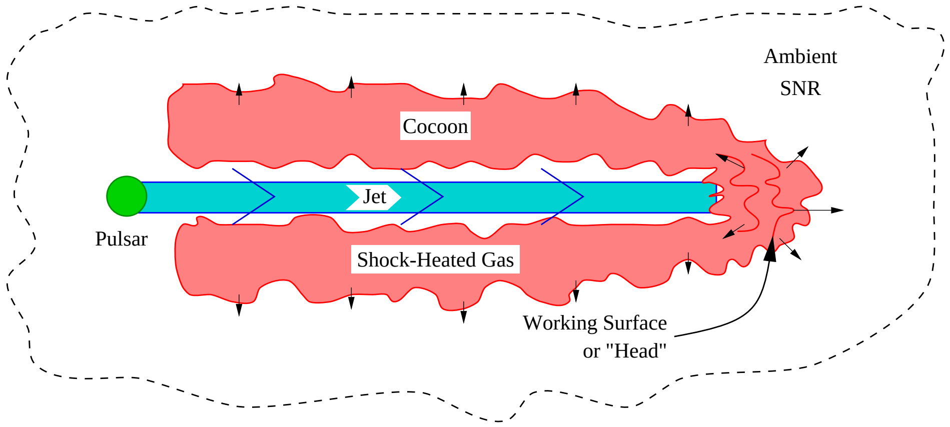

Figure 3. Cross section model of the Vela jet cocoon. The jet is a narrow collimated beam from the pulsar which interacts in a shock zone at the head. Shock-heated material expands perpendicularly to the jet axis, forming a "cocoon" of hot X-ray emitting gas which is observed.

$v_j = 800 - 1300$ km s^{-1}. We should note that these speeds are just barely supersonic in the ambient medium. The total mechanical power required to drive this jet, $\dot{E} = \frac{1}{2}A_j\rho_j v_j^3 \sim 10^{36} - 10^{37}$ erg s^{-1}, is approximately the pulsar's rotational energy loss rate. This is a powerful argument for the pulsar-jet association!

There are some difficulties with the cocoon model as well. The mass flow rate of the jet, $\dot{M}_j \sim (1-10)\times10^{-6}\,M_\odot$ yr^{-1}, is quite large. There is no way for so much mass to be extracted from the surface of a $1M_\odot$ neutron star of Vela's spindown energy; or to be swept up by the pulsar's proper motion of 100 km s^{-1} to the northwest (Ögelman, Koch-Miramond, Auriére 1989). It is conceivable that mass is being entrained along the length of the jet. Another matter of concern is the confinement of the cocoon. We find that the cocoon pressure exceeds the SNR pressure by a factor of ~ 5, and yet the cocoon has not expanded significantly in the perpendicular direction. Although magnetic fields are known to exist and be aligned along the jet axis (Milne 1995), the radio observations of Frail, et al. (1996) do not find enough magnetic pressure to confine the jet.

4. Synchrotron Model

A power law model fits equally well to the ROSAT+ASCA spectrum. If the cocoon spectrum is a power law, then we may be observing synchrotron radiation from a relativistic plasma in the presence of a magnetic field. The existence of magnetic fields in the region is well established, and radio emission from the outskirts of the cocoon region implies that some form of particle acceleration mechanism is indeed occurring (Frail, et al. 1996). Furthermore, previous non-imaging hard X-ray spectra of the Vela X region are power law instead of thermal, with similar photon indices to the ASCA result (Smith & Zimmermann 1985; Pravdo, et al. 1978). These facts push us to consider the strong possibility that the jet is a site of accelerated particles radiating by the synchrotron process.

A consistent model explaining the presence of the emission is desirable. A "first draft" of the model might be as follows. The pulsar produces a wind outflow, highly collimated by some mechanism, which emerges along its spin axis. The outflow travels outward until it interacts with the surrounding SNR gas and is shock-accelerated. It seems reasonable to assume that fresh particle acceleration is occurring along the entire length of the jet, since by our estimates the characteristic synchrotron lifetime of the electrons producing ≥ 1 keV X-rays is $\leq$5000 yr, less than the 10^4 yr age of the SNR. The knotty structure observed along the Vela jet is reminiscent of similar "hot-spot" structures seen in many extragalactic jets, and may reflect similar shock dynamics.

5. Conclusion

The primary surprise from the new ASCA results is that the jet spectrum is lacking emission line features, unless the lines are so severely blended that they form a continuum. Still, at least 50% of the emission appears to be thermal, and the energy flow in the jet remains comparable to the spindown luminosity of the pulsar, indicating that it is connected to an outflow along the rotation axis of the pulsar. With the observation of jet-like signatures associated with this and other pulsars, we suggest that jets may be more ubiquitous than previously imagined and that a search for jets around other pulsars may prove fruitful.

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