The ASCA Spectrum of the Vela Pulsar Jet

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ABSTRACT

ROSAT observations of the Vela pulsar and its surroundings revealed a collimated X-ray feature almost $45'$ in length (Markwardt & Ögelman 1995), interpreted as the signature "cocoon" of a one-sided jet from the Vela pulsar. We report on a new ASCA observation of the Vela pulsar jet at its head, the point where the jet is believed to interact with the supernova remnant. The head is clearly detected, and its X-ray spectrum is remarkably similar to the surrounding supernova remnant spectrum, extending to X-ray energies of at least 7 keV. A ROSAT+ASCA spectrum can be fit by two-component emission models but not standard one-component models. The lower energy component is thermal and has a temperature of 0.29 ± 0.03 keV (1σ); the higher energy component can be fit by either a thermal component of temperature $\sim$4 keV or a power law with photon index $\sim$2.0. Compared to the ROSAT-only results, the mechanical properties of the jet and its cocoon do not change much. If the observed spectrum is that of a hot jet cocoon, then the speed of the jet is at least 800 km s^{-1}, depending on the angle of inclination. The mechanical power driving the jet is $\geq 10^{36}$ erg s^{-1}, and the mass flow rate at the head is $\geq 10^{-6} M_{\odot}$ yr^{-1}. We conclude that the jet must be entraining material all along its length in order to generate such a large mass flow rate. We also explore the possibility that the cocoon emission is synchrotron radiation instead of thermal.

Subject headings: ISM: jets and outflows — pulsars: individual (Vela) — supernova remnants — X-rays: stars

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). A $\sim$0.5 pc diameter high energy compact nebula surrounds the pulsar (de Jager, Harding & Strickman 1996; Ögelman, Finley & Zimmerman 1993; Harnden, et al. 1985) but its X-ray luminosity is only $\sim 10^{33}$ erg s^{-1}, too small to explain the pulsar energy loss. 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 ??). They interpret the observed X-ray structure to be thermal emission from a shock-heated cocoon of gas surrounding the jet itself, and conclude that the mechanical energy required to drive the jet into the SNR interior is 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 overpredicts the jet emission when extended to lower energy X-rays.

This paper describes an ASCA observation of the “head” of the Vela jet, the point where the the jet is believed to interact with the SNR. We find that the spectrum is remarkably smooth up to 7 keV, with perhaps only one strong emission line near 1 keV. In sections 2 and 3, we describe the observations by ASCA, and present the combined ROSAT+ASCA spectrum of the cocoon. In sections 4 and 5, we compare the spectral results against candidate jet models, including the cocoon model of MÖ and a synchrotron emission model.

2. Observations and Analysis

ASCA observed the "head" of the Vela jet on 1995 April 15–16, in two separate pointings of 15 ks usable time each. SIS observations were conducted in 2-CCD Bright mode with the long chip axis oriented nearly perpendicular to the jet axis. Figure ?? shows the ROSAT image of the jet in the X-ray band 0.7–2.4 keV, with a representation of the position and orientation of the two ASCA pointings (labelled pointings A & B). The 2-CCD configuration has an $11' \times 22'$ field of view, but the pointings partially overlapped for the purpose of sampling the SNR emission on either side of the jet cocoon, leaving a net field of view of $11' \times 35'$. For both exposures, the cocoon head was primarily in the field of view of one CCD, leaving the other CCD to sample the SNR emission. ASCA is an imaging telescope, but for the purposes of this *Letter*, we have only used the spatial resolution of the instrument to distinguish between emission from the cocoon and from the patches of SNR immediately adjacent to the cocoon on the sky — which we consider to be "background." ROSAT and ASCA spectra were obtained using identical selection regions. ASCA X-ray events were screened using the criteria recommended by the ASCA Guest Observer Facility to remove periods of high particle background. Analysis was performed with the FTOOLS package, version 3.3, and with XSPEC version 9.00. Selection regions did not cross the CCD boundaries. The region including the head of the cocoon had a count rate of $(5.3\text{–}5.9)\times 10^{-3}$ ct s^{-1} arcmin^{-2} compared to the surrounding SNR count rate of $(2.6\text{–}3.8)\times 10^{-3}$ ct s^{-1} arcmin^{-2} (per CCD), where the variation is due to different CCD sensitivities.

Because the Vela SNR itself contributes about half of the observed ASCA counts from the cocoon, background subtraction is a concern. Background regions were taken from the outermost $11' \times 6'$ "wings" of the field of view where cocoon emission was the lowest. We were concerned that the jet emission could contaminate the background spectrum because of the broad PSF of the telescope. The background we observe is very similar to SNR emission seen in an archival ASCA observation of a portion of the SNR at least $30'$ from the jet (shown in Figure ??), leading us to conclude that the broad PSF of ASCA is not a significant contaminating factor. We also deem it unlikely that the effect of stray single-reflection X-ray photons from off-axis sources (including the Vela SNR itself) makes a large contribution to the cocoon spectrum, since the photons would need to be preferentially imaged onto the cocoon region in both SIS exposures of the observation. Because all of the ROSAT and ASCA spectra are self consistent where they overlap in energy coverage, we infer that any ASCA-specific contamination effects are small.

3. Spectrum

Figure ?? shows the spectrum of the SNR (lower) and cocoon+SNR (upper) as measured by both ASCA and ROSAT. The spectra are virtually identical from 0.7–7 keV except in intensity; below 0.7 keV the SNR emission dominates the spectrum. Various spectral models were fitted to the combined ROSAT/ASCA spectrum of the cocoon. Single-component models produced very poor fits and are not shown. The best fits had two components: a lower temperature thermal plasma ($T_l = 0.29 \pm 0.03$ keV $\simeq (3.4 \pm 0.3) \times 10^6$ K), and a higher energy component, which is fit by either a higher temperature plasma or power law emission. The best-fitting two-component models are presented in Table ??. The spectrum of the surrounding SNR was fit to a similar model, with the addition of a *third* thermal component, of temperature 0.14 keV and emission measure 0.46 cm^{-6} pc, to represent the contribution in the 0.1–0.7 keV range which dominates in the ROSAT soft channels. Because the third, cool, component was confined to only the lowest energy channels it had little effect on the other two hotter components. We believe that the lowest-temperature emission is from the outermost shells of the SNR and thus unimportant in the analysis of the jet, as explained in more detail below. The total unabsorbed flux from the cocoon is 1.3–1.6$\times 10^{-13}$ erg cm^{-2} s^{-1} arcmin^{-2} in the 0.1–7.0 keV band for both components, independent of the model taken, which corresponds to a luminosity of $\sim 2 \times 10^{33}$ erg s^{-1} for a $45' \times 12'$ jet at 500 pc.

EDITOR: PLACE TABLE ?? HERE.

Thermal models represent emission from an optically thin plasma at collisional equilibrium (Raymond & Smith 1977, RS), and did not change appreciably when alternate plasma models were used (Mewe, Kaastra & Liedahl 1995). The best-fit abundances are quoted in Table ??, but we cannot be certain enough about the detailed accuracy of the spectral models (especially at energies of ∼1 keV) to claim that the quoted values represent true physical abundances in the plasma.

4. Cocoon Model

We now wish to compare the spectral results to the cocoon model of MÖ. 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. A large fraction of the Vela pulsar spindown luminosity drives the outflow, which in turn goes into heating the gas and expanding the cocoon. At the observed density and temperature the gas has a much longer radiative lifetime ($\sim 10^7$ yr) than the pulsar's spindown age ($\sim 10^4$ yr) and so is not in a radiation-dominated phase. The observed X-ray emission is thus from the hot cocoon plasma and not the jet itself.

The cocoon model of MÖ requires that we know the cocoon and SNR density ratio. We estimate the electron number density from $n = \sqrt{\mathrm{EM}/fl}$, where EM is the observed emission measure, l is the line-of-sight thickness of the emitting region (which we assume to be equal to the transverse dimension as measured by the angular diameter), and f is the fraction of the volume filled by gas. Density obtained in this manner scales as $d^{-0.5}f^{-0.5}$, where d is distance.

We expect that the center of the Vela SNR is filled by the hottest plasma. Thus the hottest SNR spectral component should represent the gas at the center of the Vela SNR which surrounds the jet cocoon. The lower temperature components of the observed ASCA/ROSAT SNR spectrum would be emission from the outer, cooler shells of the SNR which are also subtended by the ROSAT and ASCA lines of sight. If we further assume that the remnant is in pressure equilibrium, then the observed emission measures indicate that the thickness of the cool shell is a factor ~ 100 times thinner than the hot centermost gas, and thus can be ignored in applying the cocoon model. The assumption of pressure equilibrium is proper as long as the gas has not begun to undergo significant radiative cooling, which as previously mentioned is the case. At the assumed SNR distance of 500 pc, the central electron density is $n_{\mathrm{SNR}} = 0.056 \pm 0.003$ cm^{-3}, where we have used a SNR angular diameter of $7.2°$ (Aschenbach, Egger & Trümper 1995).

The parameters of the cocoon depend to some extent on the angle of inclination, θ, of the jet axis to our line of sight. The length of the cocoon, for example, is 6.5 pc$/\sin\theta$ ($\propto d$). The average bow shock speed, v_h, estimated as the cocoon length divided by the pulsar age, τ, is $v_h = 570$ km s$^{-1}/\sin\theta$ ($\propto d\tau^{-1}$). The electron density of the cocoon — accounting for the effect of projection on the emission measure — is $n_c = 0.32 \pm 0.02$ cm^{-3} $\sqrt{\sin\theta}$ based on the emission measure of the hottest component. Since the sound speed of an ideal monoatomic gas at a temperature of $\sim$4 keV is $\sim$700 km s^{-1}, the bow shock can be supersonic in the SNR only if the jet is inclined to our line of sight with $\sin\theta \lesssim 0.77$. If we also assume that the jet terminates inside the SNR radius, we arrive at the approximate constraint, $10° \lesssim \theta \lesssim 60°$.

The mechanical properties of the jet can be found by considering its interaction with the surrounding remnant at the working surface. Proceeding in the same manner as MÖ, we obtain a relation for the relative jet speed as it reaches the head — v_j/v_h — in terms of the density contrast between the cocoon and the SNR. We find $1.4 < v_j/v_h < 2.3$, or in absolute terms v_j =800–1300 km s$^{-1}/\sin\theta$ ($\propto d\tau^{-1}$). The mechanical power delivered to the working surface by the jet is $\dot{E}_j = \frac{1}{2} A_j \rho_j v_j^3 = 10^{36} - 10^{37}$ erg s$^{-1}/\sin\theta$ ($\propto d^{4.5}\tau^{-3}$), which is consistent with the Vela pulsar spindown luminosity of 7×10^{36} erg s^{-1}. Since a majority of the spindown luminosity goes to heating the cocoon gas in this model, we can also estimate the average rate of energy input via heating as the time rate of change of the internal energy, or $\dot{E}_{th} = \frac{3}{2}(2n_c)kT_c V_c/\tau \simeq 10^{36}$ erg s$^{-1}/\sqrt{\sin\theta}$ ($\propto d^{2.5}\tau^{-1}$), where V_c is the volume of the cocoon. Such an estimate is again appropriate because the gas cooling timescales are much longer than the SNR's present age: all energy added to the cocoon by the pulsar is still effectively trapped there. Arriving at the same order of magnitude for the jet power by two different techniques which have different distance and age dependences, we are confident that the jet and cocoon of this model are pulsar driven.

There are some problems with the cocoon interpretation, primarily that the mass flow rate delivered by the jet beam to the working surface, $\dot{M}_j = A_j \rho_j v_j = (1 - 10) \times 10^{-6} M_\odot$ yr$^{-1}/\sin\theta$ ($\propto d^{2.5}\tau^{-1}$), is quite large. There is no way for so much mass to be extracted from the surface of a $1 M_\odot$ neutron star with an energy budget of 7×10^{36} erg s^{-1}. It is also more than the pulsar could have swept up via its proper motion of 100 km s^{-1} to the northwest (Ögelman, Koch-Miramond, Auriére 1989; Bailes, et al. 1990) through a plasma with density $n_{\rm SNR}$. Additional material may be entrained along the length of the jet, converting the jet from a presumably relativistic outflow originating at the pulsar, to a slow heavy massive jet when it reaches the working surface. Considering that the jet axis is nearly perpendicular to the pulsar proper motion direction the jet may indeed be sweeping up SNR material all along its length. Because the derived jet speed is barely supersonic and the temperatures of the cocoon and SNR are indistinguishable, within errors, this seems to be the most favorable interpretation of the cocoon model.

The cocoon also appears to be too highly collimated for a canonical jet interaction. Typical jet cocoons expand in the transverse direction because they are overpressured, and are narrower at the head than at the power source, since the oldest portion of the cocoon is nearest the source and thus has had the most time to expand. The Vela cocoon as measured in X-rays has a pressure of $\sim 4 \times 10^{-9}$ erg cm^{-3} — much larger than the surrounding SNR pressure of $\sim 1 \times 10^{-9}$ erg cm^{-3} — and yet appears to be cylindrical with no widening near the pulsar. Although magnetic fields are known to exist and be aligned along the jet axis (Milne 1980, 1995), the radio observations of Frail, et al. (1996) do not find enough magnetic pressure to confine the jet transversely either.

5. Synchrotron Model

The 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 laws, with photon indices ranging between 2.1–2.3 (Smith & Zimmermann 1985; Pravdo, et al. 1978), and are compatible with our ASCA spectra of both the cocoon and the SNR. Finally, when we examine the ROSAT data for the full 1° field surrounding the pulsar, we find a large region covering 70–80% of the field which has a spectrum similar to our ASCA spectrum (at least, to the sensitivity level possible with ROSAT). These facts push us to consider the strong possibility that the center of the Vela SNR — and the jet in particular — 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 $\lesssim$5000 yr, less than the 10^4 yr age of the SNR. We find it unlikely that the particles could be confined to the jet region by any external pressure once they are accelerated. As mentioned previously, the exterior thermal and magnetic pressures in the SNR are not enough to contain expansion. We expect that the relativistic particles will diffuse outward, perhaps to fill a large interior portion of the SNR. This may also explain why we observe a large region of hard X-ray emitting plasma with ROSAT and the presence of a power law in the ASCA SNR spectrum. The jet region has the highest density of accelerated particles (since it is the source), and thus radiates with the highest intensity; particles which diffuse into the lower-density surroundings also emit synchrotron radiation, but at a lower intensity.

6. Conclusion

We have detected emission from the Vela pulsar jet cocoon with the ASCA X-ray telescope. It is at least partially thermal with a peak near 1 keV, but has a smooth spectrum above that energy which extends to at least 7 keV. The derived cocoon-model quantities for the jet have not changed much compared to the

ROSAT-only results of MÖ, but it has now become clear that the spectrum is not a single plasma or power law emission model, but rather has at least two components.

There are some other uncertainties which need to be resolved. The cocoon model parameters quoted in this paper depend to a large extent on accurate determinations of the pulsar distance and age. While the "canonical" distance for the Vela pulsar has been long quoted as 500 pc, there have been claims by Jenkins & Wallerstein (1995) that this distance is not entirely compatible with the standard model of SN energetics. Their optical observations of blast wave filaments are more consistent with a distance of 250 pc. As to the Vela pulsar's age, we have used the spindown age of $\tau = P/2\dot{P}$, which assumes a braking index of $n = 3$. Lyne, et al. (1996) have recently obtained a braking index of $n = 1.4 \pm 0.2$ by examining the history of $\dot{\nu}$ over a time baseline of 25 yr which includes nine major glitch events. If correct, this result implies that the pulsar could be as much as two to three times older than the spindown age. If either the distance were smaller than 500 pc or the age of the pulsar were more than 10^4 yr, then the derived jet speed, v_j would become slower by the ratio d/τ, which would reduce the mechanical power of the jet in the cocoon model significantly.

The SNR and cocoon spectra are nearly identical. Although this might suggest that the observed jet is merely a high density filament in the SNR, we are convinced that the jet is truly a pulsar-powered phenomenon, on the basis of the following arguments. (1) Most of the filaments in the Vela SNR have temperatures in the range 0.1-0.2 keV (MÖ; Kahn, et al. 1985), and yet the jet cocoon has at least one component whose temperature is 3–4 keV. (2) The jet appears to emerge along the pulsar spin axis, the only symmetry axis which is fixed in time (Radhakrishnan & Cooke 1969). (3) If the cocoon model is applied, then the mechanical power of the jet is comparable to the pulsar spindown luminosity. (4) The thermal energy stored in the cocoon is consistent with the pulsar spindown energy. (5) The image of MÖ clearly shows that the starting point for the jet is at the pulsar's present-day position rather than its birthplace. This last fact also argues against the possibility that Vela's progenitor star generated the jet structure before the supernova — say, as a wind interacting with the ISM. Any such structure would be connected to the pulsar's *birthplace*, roughly $8'$–$10'$ to the southeast (Ögelman, et al. 1989; Bailes, et al. 1990) and not today's position.

We have planned an additional observation by ASCA of the remainder of the jet, which is yet unobserved, in order to determine whether the spectral properties of the jet vary along its length. We note, for example, the recent results of Tamura, et al. (1996), who find a hot nebula with ASCA near PSR 1509–58 in the SNR MSH 15–52. They observe a non-thermal X-ray feature extending linearly from the pulsar and a hot thermal plasma "cloud" at the end of the jet feature, which shows line emission by magnesium. They interpret the observations as a relativistic stream of particles generated by the pulsar, radiating synchrotron emission, and upon interaction with the ambient material at the end of the jet, also radiating thermal emission by shock heating. Our observations show that the Vela jet is also radiating thermal emission from the head, in particular by neon. At present we do not know if the thermal emission extends over the length of the Vela jet, or — as in MSH 15–52 — is confined to the head only. Future work by ASCA should determine this.

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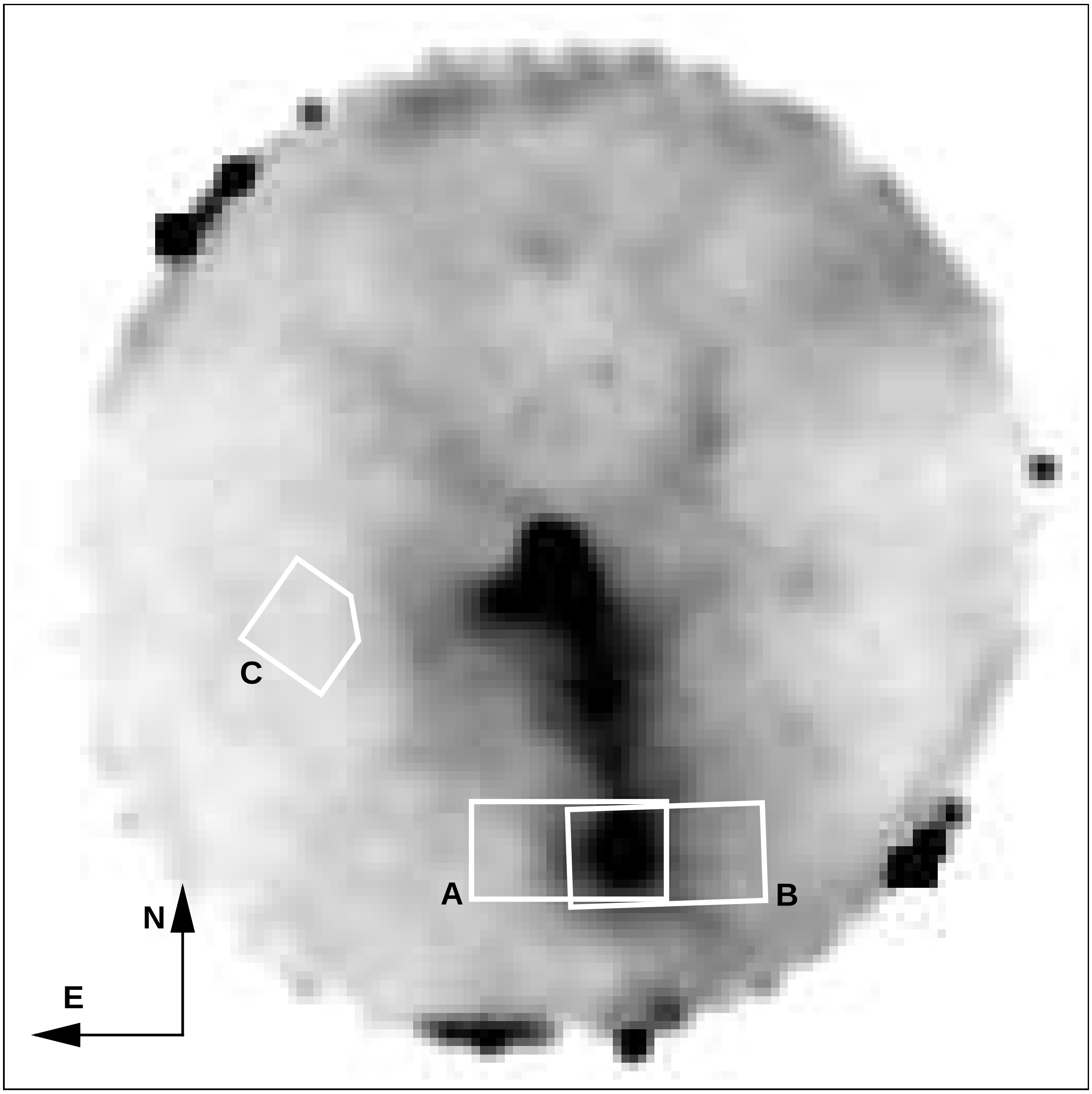

Fig. 1.— Image of the Vela pulsar and its 1°-radius surrounding field, as obtained by ROSAT in the 0.7–2.4 keV X-ray band. The jet projects from the pulsar (at center) to south-southwest ∼45′. The ASCA fields used in this work are indicated as white boxes: (A) & (B) are observations of the jet; (C) is an archival observation (sequence 50021010) of the Vela SNR used for additional background measurements. The centers of fields (A) and (B) were, respectively, $\alpha(2000)=08^{\rm h}34^{\rm m}55^{\rm s}$, $\delta(2000)=-45°52'13''$, and $\alpha(2000)=08^{\rm h}33^{\rm m}56^{\rm s}$, $\delta(2000)=-45°52'13''$.

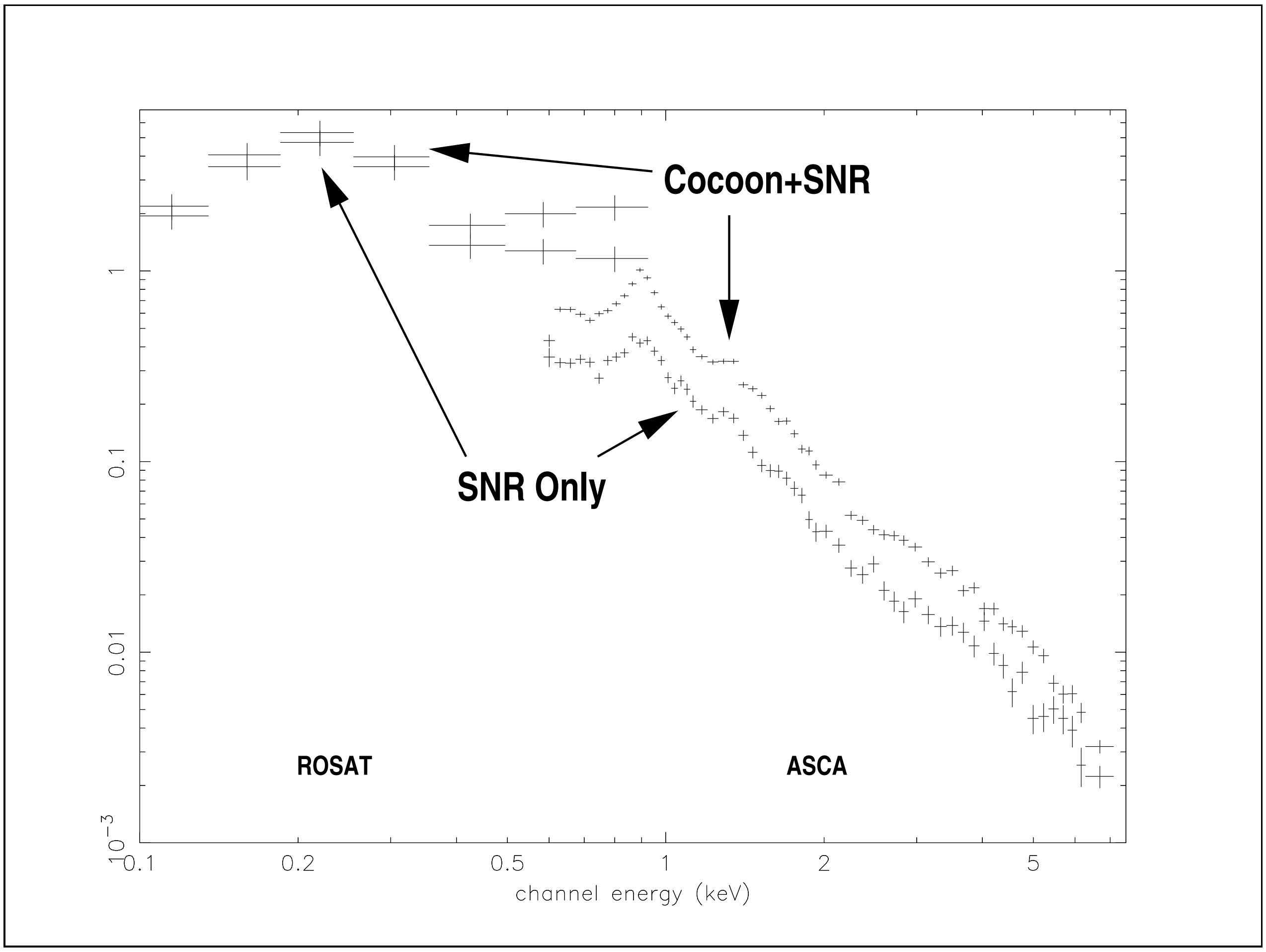

Fig. 2.— Combined ROSAT and ASCA spectra of the Vela jet+SNR *vs.* SNR alone, in units of cts s^{-1} keV^{-1} per SIS CCD solid angle of 11×11 $arcmin^2$. The ROSAT spectra range from 0.1–0.9 keV, and are represented by the wide data bins; the ASCA spectra range from 0.6–7.0 keV and are represented by narrow bins. The jet is the more intense (upper) spectrum, as indicated by the arrows. The ROSAT and ASCA count rate spectra do not match between 0.6 and 0.9 keV because of differing instrumental response.

Table 1. Spectral Parameters for Vela Jet Cocoon & SNR

Parameter	Cocoon	SNR[a]	Approx. 1σ errors
N_H (10^{20} cm^{-2})[b].......	2.6	2.6	
1 Temperature plasma + Power law			
kT_l (keV)[c].............	0.29	0.33	±0.03
EM$_l$ (cm^{-6} pc)	0.15	0.13	±0.03
PL photon index........	2.11	2.08	±0.15
PL flux[d]................	9.85	10.8	±1.65
[Ne][e]....................	1.65	1.08	±0.50
[O]	0.50	0.42	±0.12
[Fe]	0.20	0.23	±0.08
χ^2 (d.o.f.)	320.4 (239)	570.5 (403)	
2 Temperature plasma			
kT_l (keV)[c].............	0.29	0.34	±0.03
EM$_l$ (cm^{-6} pc)	0.28	0.20	±0.10
kT_h (keV)[c].............	3.74	4.48	±0.90
EM$_h$ (cm^{-6} pc)	0.18	0.19	±0.02
[Ne][e]....................	0.92	0.82	±0.40
[O]	0.28	0.39	±0.12
[Fe]	0.13	0.18	±0.08
χ^2 (d.o.f.)	327.4 (239)	617.3 (403)	

[a]A third component was needed to fit the SNR spectrum, as described in the text.

[b]Parameter was fixed (Harnden et al. 1985).

[c]The subscripts l and h refer to the low and high temperature components respectively.

[d]Unabsorbed incident flux in the 0.1–7.0 keV energy range, in units of 10^{-14} erg cm^{-2} s^{-1} arcmin^{-2}.

[e]Elemental abundances are given w.r.t. solar abundance. Unlisted elements were fixed at solar abundance.