The jets of the Vela pulsar.

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Abstract

Chandra observations of the Vela pulsar-wind nebula (PWN) have revealed a jet in the direction of the pulsar’s proper motion, and a counter-jet in the opposite direction, embedded in diffuse nebular emission. The jet consists of a bright, $8''$-long inner jet, between the pulsar and the outer arc, and a dim, curved outer jet that extends up to $\sim 100''$ in approximately the same direction. From the analysis of thirteen Chandra observations spread over $\approx 2.5$ years we found that this outer jet shows particularly strong variability, changing its shape and brightness. We observed bright blobs in the outer jet moving away from the pulsar with apparent speeds (0.3–0.6) $c$ and fading on time-scales of days to weeks. The spectrum of the outer jet fits a power-law model with a photon index $\Gamma = 1.3 \pm 0.1$. For a distance of 300 pc, the apparent average luminosity of the outer jet in the 1–8 keV band is about $3 \times 10^{30}$ erg s$^{-1}$, compared to $6 \times 10^{32}$ from the whole PWN within 42$''$ from the pulsar. The X-ray emission of the outer jet can be interpreted as synchrotron radiation of ultrarelativistic electrons/positrons. This interpretation allows one to estimate the magnetic field, $\sim 100 \mu$G, maximum energy of X-ray emitting electrons, $\sim 2 \times 10^{14}$ eV, and energy injection rate, $\sim 8 \times 10^{33}$ erg s$^{-1}$, for the outer jet. In the summed PWN image we see a dim, $\sim 2'$-long outer counter-jet, which also shows a power-law spectrum with $\Gamma \approx 1.2$–1.5. Southwest of the jet/counter-jet (i.e., approximately perpendicular to the direction of pulsar’s proper motion), an extended region of diffuse emission is seen. Relativistic particles responsible for this radiation are apparently supplied by the outer jet.

Key words: ISM: jets and outflows — pulsars: individual (Vela) — stars: neutron — stars: winds, outflows — supernova remnants: individual (Vela) — X-rays: stars

1 Introduction

Recent detailed images obtained with Chandra for PWNe around the Crab pulsar (Hester et al. 2002), Vela pulsar (Helfand et al. 2001; Pavlov et al. 2001), and PSR B1509–58 (Gaensler et al. 2002) have shown approximately
axially-symmetric PWN morphologies, with an extended jet-like structures stretched along the symmetry axis. This suggests that the jets are common to at least young pulsars and are not limited to accreting systems (e.g., AGNs, microquasars). Most likely, pulsar jets are associated with collimated outflows of relativistic particles along the pulsar’s rotation axes.

Due to its proximity \((d \simeq 300 \text{ pc}; \text{Caraveo et al. 2001})\), the Vela PWN is particularly well suited for studying the pulsar outflows. We carried out a series of eight monitoring observations with the Chandra Advanced CCD Imaging Spectrometer (ACIS). These observations have confirmed the dynamical structure of the PWN (Pavlov et al. 2001), with most dramatic changes occurring in the outer jet. Moreover, we were able to detect an “outer counter-jet”, a much dimmer extension of the southeast (counter-)jet. Here, we focus on the highly variable outer jet, which has been detected in ten ACIS observations (carried out from 2000 April 30 through 2002 August 6) and three observations with the High Resolution Camera (HRC).

2 Results

The large-scale X-ray structure of the Vela PWN is shown in the summed image composed of the last eight ACIS observations (upper left panel of Fig. 1; see Pavlov et al. 2002 for technical details of the observations, image reduction and co-alignment). This deep image clearly reveals a long outer jet \([7]\), approximately in the direction of the proper motion \((\text{PA} \simeq 307^\circ; \text{Caraveo et al. 2001})\). The outer jet extends for \(\approx 1\, \farcs7 = 0.14 \, d_{300} \) pc away from the pulsar, where \(d_{300}\) is the distance to the pulsar in units of 300 pc. The characteristic width (diameter) of the outer jet is about \(3 \times 10^{16} d_{300} \) cm. A much fainter outer counter-jet \([8]\) is seen in the opposite direction. Also, we see extended diffuse emission \([9]\) southwest of the jet/counter-jet line, which is obviously connected to the “main body” of the PWN. The inner PWN with the pulsar \([1]\) at its center consists of the inner arc \([2]\), the outer arc \([3]\), the inner jet \([4]\), and the inner counter-jet \([5]\). The inner jet is directed northwest from the pulsar in the direction of the pulsar’s proper motion, and the counter-jet is directed toward the southeast \((\text{PA} \simeq 127^\circ)\). The bright PWN core (white in Fig. 1) is surrounded by a “shell” \([6]\) of diffuse emission. The outer jet looks like an extension of the much brighter inner jet, well beyond the apparent termination point of the inner jet at its intersection with the outer arc. Finally, Figure 1 demonstrates that the outer jet preferentially bends to the south-west of the jet/counter-jet line and apparently connects to the extended diffuse emission region (Fig. 1; upper left panel).

Figure 1 also presents the time sequence of the ACIS-S3 and HRC-I observations for the outer jet. The variability of the outer jet is clearly seen, in
both the HRC and ACIS images. Over the thirteen observations, with different periods of time between each of them, we distinguish three different types of variability. First, the outer jet shifts from side to side, bending and apparently twisting. Second, the blobs move outward along the outer jet. Finally, the blobs change in brightness and eventually disappear.

The most dramatic variations we see are the large-scale bends of the jet (e.g. compare observations 1, 2, 3 and 13 in Fig. 1). The short time (16 days) between the fifth and eighth observations suggests that this bending occurs on a time scale of order of weeks. The small-scale changes are seen in all of the observations. For instance, the “base” of the outer jet (where it leaves the shell — see the white boxes in Fig. 1 in upper right and bottom panels) shifts from one observation to the next. Typical apparent speeds of these shifts are of order a few tenths of speed of light. The apparent speeds of blobs A and B are \((0.35 \pm 0.06) c\) and \((0.51 \pm 0.16) c\), respectively. Blob C vanished quickly, having an (unconstrained) apparent speed of \((0.6 \pm 0.7) c\). Thus, the observed variations suggest typical bulk flow velocities of 0.3–0.7 of the speed of light.

The outer jet is, on average, a factor of 7 brighter than the outer counter-jet. If the outer jet and outer counter-jet are intrinsically similar but streaming along a straight line (on average) in opposite directions, then the difference in brightness means that the outer jet is approaching at an angle of \(30^\circ–70^\circ\) to the line-of-sight while the outer counter-jet is receding. Such an orientation contradicts the previously suggested models of the inner jets and the bright arcs (e.g. Helfand et al. 2001).

We see that the width of the outer jet, \(\sim 3 \times 10^{16} \text{ cm}\), remains approximately the same along the jet in all observations. This suggests an efficient confinement mechanism, perhaps associated with magnetic fields generated by electric currents in the pinched jet. The current required, \(\sim 10^{32} \text{ e s}^{-1} \sim 10^{12} \text{ amp}\), is an order of magnitude lower than the Goldreich-Julian current in the pulsar magnetosphere. The bright blobs and strong bends could be caused by the sausage and kink instabilities, respectively, in such a pinched jet.

The spectrum of the outer jet fits well with a power law model \((\Gamma = 1.3 \pm 0.1)\) suggesting the synchrotron emission. The outer counter-jet also exhibits power-law spectrum with \(\Gamma \approx 1.2–1.5\). Outside the bright PWN, there is an asymmetric, dim outer diffuse nebula that is substantially brighter southwest of the jet/counter-jet line. Its spectrum \((\Gamma \approx 1.5)\) is softer than that of the outer jet, but it is harder than the spectrum of the brighter PWN shell \((\Gamma \approx 1.65; \text{ region} \ [6] \text{ in upper left panel of Fig. 1})\). Thus, it is possible that the X-ray emitting particles in the dim nebula are supplied through the outer jet.

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Fig. 1. **Top left:** The summed ACIS-S3 image of the Vela PWN ($4'7 \times 4'$) total exposure time about 160 ks). **Top right and bottom:** Sequence of *Chandra* images of the outer jet. Panels 1, 2, and 10 are the HRC-I images; the rest are ACIS-S3 images. The size of each panels is $73'' \times 53''$. The boxes, $28'' \times 2'6$, at the same sky position in all the panels, are overplotted to guide the eye.

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