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Finest persistent structures in the Vela PWN

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Abstract. Based on eleven 40 ks *Chandra* ACIS observations of the Vela pulsar wind nebula (PWN) we discuss the small-scale structure of the inner PWN: a *Bright Spot* on the outer arc, a *Bar* at the base of the south-eastern jet, and a *Knot* between the pulsar and the Bar. These features can be used to understand the complex 3D structure of the outflow.

1. Introduction

The X-ray PWN of the young Vela pulsar has a complex morphology (Pavlov et al. 2001). The most prominent features are two arcs and two jets (see Fig. 1). High-resolution *Chandra* ACIS observations have revealed three fine features of the PWN. The *bright spot* appears where the NW jet visually intersects the outer arc. A feature resembling a thin *bar* perpendicular to the SE jet lies at the jet's base. A bright *knot* of emission in hard X-rays is seen between the pulsar and the bar.

Kargaltsev et al. (2008) reported on the fine dynamical feature at the SE jet base. It lies $\approx 6''$ from the pulsar and is shaped as a thin $1\farcs5 \times 4\farcs8$ bar perpendicular to the jet. The Bar is likely similar to the Knot 2 in the dynamical *sprite* feature at the base of the Crab pulsar jet (Hester et al. 1995). To suppress the bright but soft pulsar emission, we also produced a hard band (1.5–8 keV) image and found a bright, unresolved 'Knot' located $1\farcs8$ from the pulsar. Note that in the high-resolution *HST* images of the Crab nebular Hester et al. (1995) found an 'Inner Knot' just $0\farcs65$ from the pulsar in the direction of the jet. This allows us to assume that such features are not unique for Crab and Vela but exist in many young PWNe; their nature is still to be studied.

Meanwhile, synchrotron emission maps of PWNe built upon RMHD simulations of pulsar winds exhibit similar structures (e.g., del Zanna et al. 2006; Komissarov & Lyutikov 2011; Camus et al. 2009). The bright central knot is attributed to fluid escaping toward the observer from the polar cusp-like region immediately downstream of the oblate termination shock (TS). If the simulations capture the relevant physics, then the Vela Knot discovery suggests that the SE jet points toward us, an assumption also supported by our modeling of the NW jet (Durant et al. 2013). The maps also show a bright variable structure alike the Crab *sprite*. It arises from the highly variable flow at the jet base and breaks into separate knots and *bars* created via usteady non-uniform axial magnetic pinch. This variability is interpreted as development of the 'sausage'

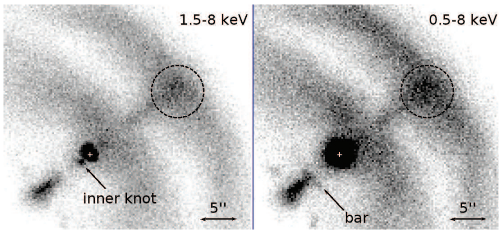

Fig. 1. The Vela PWN morphology in X-rays: the Vela pulsar (marked by the cross), the bright knot $\sim 1''.8$ SE of the pulsar, the Bar at the base of the SE jet and the bright spot (encircled with dashes). The outer segment of the NW jet is not shown here.

instability enhanced by highly inhomogeneous backflows and converging magnetosonic compression waves originating in the dynamically active region around the equatorial outflow.

The tilts of the Crab's and Vela's tori to the sky plane are similar, $\approx 61°$- $63°$. So are the angular extents of their semi-major axes, $11''.3$ (Crab) and $12''.5$ (Vela), if Vela's Inner Arc is assumed to be a Doppler-brightened part of the toroidal TS. Since the Crab is ~7 times farther, the linear extent of Vela's TS is a factor of 7 smaller than that of Crab's Inner Ring. This ratio is close to $(\dot{E}_{\rm Crab}/\dot{E}_{\rm Vela})^{1/2}$=8.2, as if the differences in the ambient pressure, $p_{\rm a}$, and other factors were relatively unimportant in this respect. Should the PWN structure be only dependent on $\dot{E}/p_{\rm a}$ and the inclination, one could expect the Crab and Vela PWNe images to be very similar There are, however, obvious differences between their morphologies.

The difference between Crab's single-ring and Vela's double-arc structures has been attributed to wider angle between the pulsar spin and the magnetic dipole axis in the Vela pulsar (e.g., Harding et al. 2008; Radhakrishnan et al. 2001). RMHD models suggest the same. The wider angle leads to more extended low magnetization region in the pulsar wind around the rotational equator, and to less efficient magnetic hoop stresses. The latter result in a more diffusive nebular emission, a more complex system of rings and arcs in the inner region, and a much shorter brightened segments of the jets (see, e.g., Fig.2 in del Zanna et al. 2006).

Our observations also favour this picture. The TSs radii are R_V = 6.6×10^{16} cm (Vela) and R_C = 4.6 × 10^{17} cm (Crab). The de-projected linear offsets of the Knot and Inner Knot are $0.3R_V$ and $0.1R_C$. If the knots originate near the TS cusp, the shock in Vela is less oblate, and the axial pinch is therefore weaker, than in Crab. The surface brightness of the SE Vela jet starts to decrease dramatically at the distance $\sim 10''$ from the pulsar; in the Crab jet this occurs at $\sim 22''$. When de-projected, the jet brightened parts range in (0.9-3.4) R_V (Vela) and (0.6-1.8) R_C (Crab), i.e., in Vela it is much shorter, in accordance with the RMHD models.

We briefly note about another Vela PWN element, the "Bright Spot". Whether its brightness adds up to the sum of local surface brightnesses of the outer arc and the NW jet can not be derived unambiguously: the arc brightness varies along the arc, and the jet is expected to change dramatically at about the same distance where we see the Spot. Note, that according to the commonly cited models jets and tori do not physically intersect and hence there can be no arc-jet interaction. On the other hand, emission associated with plasma dynamics in the inner tori of PWNe should exhibit a bright feature similar to the Spot, as results from RMHD modelling (Volpi et al. 2009). If further studies confirm the physical relevance of these models, the Spot can be used to infer on the bulk flow speed in the Vela PWN.

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