The Vela Pulsar and its Synchrotron Nebula: Surprises from Chandra

G. G. Pavlov, D. Sanwal, O. K. Kargaltsev, G. P. Garmire (*Penn State*), V. E. Zavlin, V. Burwitz (*MPE, Garching*), R. N. Manchester (*ATNF, CSIRO*), R. G. Dodson (*Univ. of Tasmania*)

Abstract

We report the results of the spectral and timing analysis of seven observations of the Vela pulsar and its synchrotron nebula with the *Chandra* X-ray Observatory. The pulsar spectrum in the observed 0.25–8 keV band consists of two distinct continuum components. The softer component can be modeled as either a magnetic hydrogen atmosphere spectrum with $kT_{\rm eff,\infty} = 59 \pm 3$ eV, $R_\infty = 15.5 \pm 1.5$ km, or a standard blackbody with $kT_\infty = 129 \pm 4$ eV, $R_\infty = 2.1 \pm 0.2$ km (the radii are for a distance of 250 pc). The harder component, modeled as a power-law spectrum, gives photon indices depending on the model adopted for the soft component: $\gamma = 1.5 \pm 0.3$ for the magnetic atmosphere soft component, or $\gamma = 2.7 \pm 0.4$ for the blackbody soft component. Timing analysis shows three peaks in the pulse profile, separated by about 0.3 in phase. Energy-resolved timing provides evidence for pulse profile variation with energy. The higher energy ($E > 1.5$ keV) profile shows higher pulsed fraction and only two peaks. Identification of the peaks with thermal and non-thermal components allows us to compare the X-ray profiles with the hard X-ray and γ-ray profiles and constrain the mechanisms of the pulsar radiation and the geometry of the pulsar magnetic field.

Thanks to its superb angular resolution, *Chandra* reveals the complex morphology of the Vela pulsar-wind nebula (PWN), reminiscent of that of the Crab PWN. It includes a $10''$-long bright jet at a position angle of 127°, and a fuzzy counter-jet at P.A.$=307^\circ$, very close to the position angle of pulsar's proper motion. The PWN is nearly symmetrical with respect to the jet direction that can be associated with the orientation the pulsar's spin axis. It has a bright bow-shaped front edge (outer arc), presumably a brightened part of a tilted ring of a $25''$ radius. The pulsar is enveloped by a smaller torus-like nebula of a $30''$ maximum size, with brightened front and back edges. We also see two "knots" close to the termination point of the jet. Spatially resolved spectroscopy shows that the power-law spectra of the PWN elements (arcs, jets, knots) have different slopes, with the photon index varying from 1.2 to 1.6. Measuring the photon indices and fluxes from the PWN elements enables us to estimate the magnetic fields inside the PWN, $B = 10$–$100\ \mu$G. Comparison of different observations shows temporal changes up to 30% in the surface brightness of the PWN features. Some of the PWN elements show appreciable shifts, up to a few arcseconds ($\sim 10^{16}$ cm), and/or spectral changes. We will discuss possible interpretations of the PWN morphology and variability.

CATEGORY: SUPERNOVAE, SUPERNOVA REMNANTS AND ISOLATED NEUTRON STARS