## PAST and CURRENT RESEARCH

**Craig Bishop Markwardt**

## INTRODUCTION

As a Ph.D. candidate for Hakkı Ögelman, I have become a scientifically productive and collaborative X-ray astronomer, focusing on the interaction between isolated pulsars and their surroundings. Highlights of my graduate research include studies of :

- the Vela pulsar;
- the conversion of "spindown power" into a pulsar outflow;
- X-ray observations of a jet from the Vela pulsar;
- radio observations of the Vela jet interaction; and
- high resolution X-ray imaging of the Vela pulsar wind interaction.

My graduate career has provided several valuable experiences, in collaboration with researchers in the field and as graduate student PI on *ROSAT* and *ASCA* projects.

## The VELA PULSAR and PULSAR SPINDOWN

I have concentrated on the Vela pulsar and its supernova remnant (SNR) for my thesis, but the lessons learned are applicable to the general problem of pulsar spindown and wind nebulae. It is clear that isolated pulsars — including Vela — continuously lose rotational energy, but that only a small fraction of the spindown power is accounted for by direct radiation from the pulsar. The general theoretical consensus is that the remainder leaves the pulsar via a relativistic pair-plasma and magnetic wind, but the precise details of the wind, such as its composition and generation are poorly understood. The study of pulsar outflows is important because it tests physics at the extreme, since pulsars are laboratories which sustain intense magnetic and gravitational fields that cannot be found on earth. The streaming wind particles do not radiate, so to probe the outflows we must find the signatures of their interaction with the ambient medium. The Vela pulsar is ideal for such studies because it is one of the nearest young pulsars active from radio to $\gamma$-rays and has a low absorbing neutral hydrogen column density.

## The VELA JET

The Vela jet appears in 0.7–2.4 keV *ROSAT* X-rays as a $45'$ elongated structure (Figure 1). Diffuse X-ray emission had been previously detected from the region southwest of the pulsar by *EINSTEIN* (Harnden et.al. 1985, ApJ 299, 828), but the *ROSAT* observation is the first to reveal that the feature is narrow, collimated, and remarkably symmetrical. Other researchers missed the jet structure in the *ROSAT* band because the soft X-ray SNR emission below 0.7 keV dominates the jet in a broad-band image. When I generate a narrow-band image the structure is strikingly obvious. Since the morphology of the $12'$ wide (FWHM) structure is center-filled and not shell-like, and the spectrum is consistent with thermal emission, I interpret the structure to be a "cocoon" of hot plasma formed by a pulsar jet interacting with the ambient SNR material. A simple kinematic model of this interaction which I constructed shows that the mechanical power required to drive the jet is a significant fraction of the pulsar's spindown power of $7 \times 10^{36}$ erg s$^{-1}$, implying that it is indeed the result of a pulsar-driven outflow.

I continue the study of the jet with observations by *ASCA* and the *ROSAT* High Resolution Imager (HRI). My extracted *ASCA* spectrum, of much higher resolution than the *ROSAT* spectrum, showed that the "tip" of the cocoon — the point where the jet should be interacting with the SNR — has two spectral components. There is a low-temperature thermal component ($\sim$0.3 keV) and a higher energy continuum which extends to at least 7 keV. The kinematic parameters of the cocoon model are not altered significantly. This work is submitted for publication, and additional observations are scheduled which should complete the *ASCA* coverage of the cocoon (as a test for spectral variations along its length). My project to map the cocoon with the HRI will also be completed within the coming *ROSAT* observing cycle.

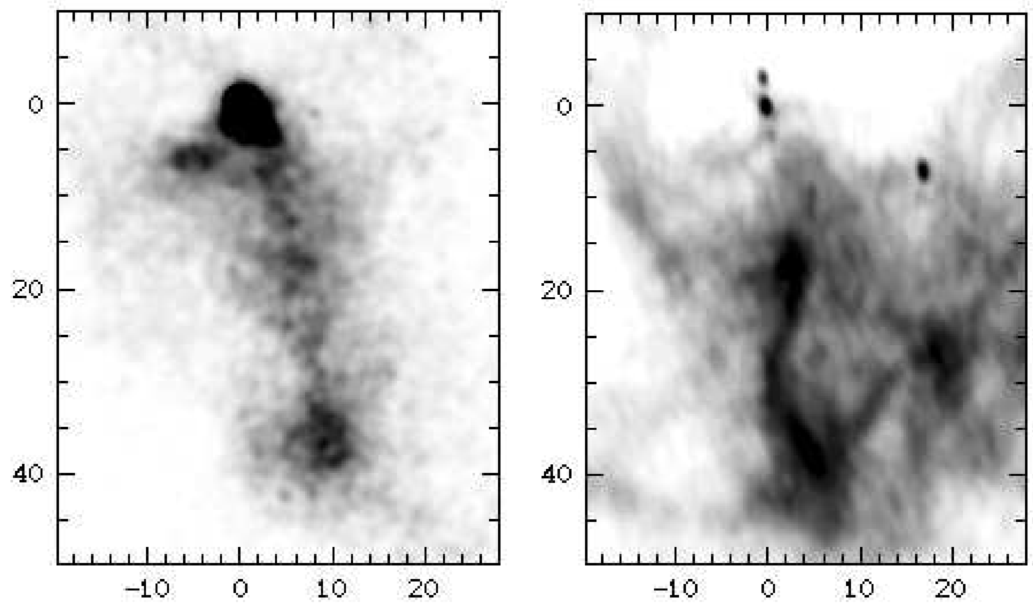


Figure 1: X-ray (left; 0.7–2.4 keV) and radio (right; 90 cm) images of the Vela X region. The X-ray jet is center filled, while the radio emission appears to form a "sheath" around the X-ray jet. The pulsar is at coordinate (0,0), measured in arcminutes.

## VLA OBSERVATIONS of VELA JET

We were very excited about the Vela jet, and embarked on a collaboration with Dale Frail and Michael Bietenholz to do a matched-resolution study of the radio emission in the vicinity of the pulsar. At the time of our 1995 *Nature* paper, we knew that the maximum of radio emission — Vela X — was concentrated near the termination point of the X-ray cocoon. I performed the initial data reduction of the 330 MHz data and had a role in the revision of the manuscript, which is accepted for publication in ApJ. The new VLA maps that we produced show that in radio there is a bright filament which traces from the pulsar southward to the center of Vela X. The geometry is reminiscent of a cylindrical sheath or shell around the X-ray cocoon (see Figure 1). At present it is not clear whether the radio emission is produced by shocked electrons accelerated in situ or by the compressed pulsar wind.

## VELA COMPACT NEBULA

The Vela pulsar has been known to have a $\sim 2'$-diameter hard X-ray compact nebula surrounding it since a 1985 observation with *EINSTEIN*, but its morphology was not fully resolved. Hakkı and I are working jointly with Fred Seward using the *ROSAT* HRI to image the nebula and perform pulsar timing. While Fred has concentrated on the timing aspect, I have constructed a very deep X-ray image of the nebula with $4''$ resolution. It is clear now that the nebula has the shape of a *bow shock* and is not spherically symmetric as is classically envisioned (Figure 2). The position angle of the bow shock apex is consistent with the observed optical proper motion of the pulsar (as determined by myself, using HST observations, and others). I conclude that the pulsar must be moving supersonically through the ambient medium, producing a ~spherical wind which interacts at a shock front to form the characteristic bow shock shape. This is perhaps the most exciting part of my work because it should provide a direct probe of pulsar wind physics. This is work in progress — one more HRI observation has been obtained — and I expect it to be a very fruitful area of research.

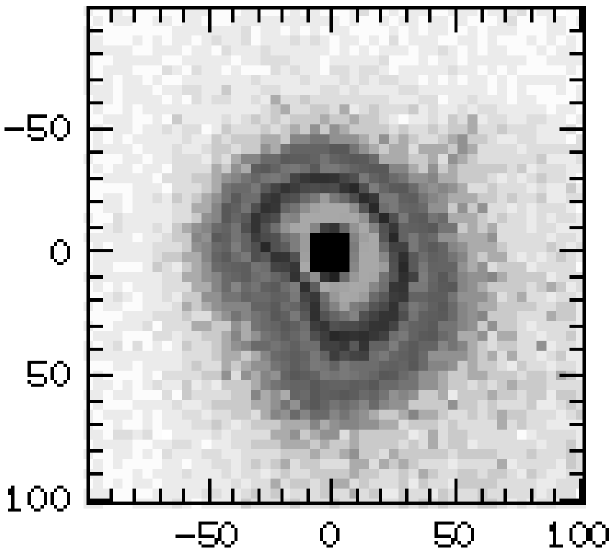


Figure 2: False greyscale *ROSAT* HRI image of the Vela pulsar and X-ray compact nebula. The nebula has the shape of a bow shock, and is consistent with the independently determined proper motion of 100 km s$^{-1}$ to the northwest (upper right). The pulsar is at coordinate (0,0), measured in arcseconds. The false greyscale is use to increase contrast; in reality the intensity decreases monotonically from the pulsar.