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Year-scale Morphological Variation of the X-ray Crab Nebula

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Abstract. We present year-scale morphological variations of the Crab Nebula revealed by the *Chandra X-ray Observatory*. Observations have been performed about every 1.7 years over the three years from launch. The variations are clearly recognized at two sites: the torus and the southern jet. The torus, which had been steadily expanding until 1.7 years ago, now appears to have shrunk in the latest observation. Additionally, the circular structures seen to the northeast of the torus have decayed into several arcs. On the other hand, the southern jet shows the growth of its overall kinked-structure. We discuss the nature of these variations in terms of the pulsar wind nebula mechanism.

1. Introduction

The five-month monitoring observations of *Chandra* and *HST* showed short-term (days to weeks) morphological variations of the Crab Nebula (Mori et al. 2002; Hester et al. 2002). A variable inner ring and wisps emerging from it visually revealed the existence of the termination shock of the pulsar wind and its downstream flow, respectively. In addition to such short-term, therefore more noticeable, variations, expansion of the outer torus on longer time-scales (months) was also discovered. However, this seems to contradict the fact that the angular extent of the torus has been almost constant over 25 years (Mori et al. 2002); if the torus kept expanding at the observed rate, it would have become almost twice larger during this period. On the other hand, the southern jet did not show a strong variation of its overall structure. This differs from the highly variable jet of the Vela pulsar (Pavlov et al. 2003), which is an another famous example of a variable pulsar wind nebula (PWN). Here we present long-term (years) morphological variations of the Crab Nebula which are newly discovered, resulting from comparison of *Chandra* observations over three years.

2. Observations

The Crab Nebula has been observed by several PIs with different objectives. The first observation was performed just after launch (Weisskopf et al. 2000) and the latest one was done 3.3 years after that to witness the transit of Titan, Saturn's largest moon, across the Crab Nebula (Mori et al., in preparation). In this paper, we used those two observations, as well as one of the monitoring observations which were performed almost at the midpoint of the first and latest ones. Hereafter, we refer to these as first, second, and third epoch observations. They are roughly spaced at 1.7-year intervals. Table 1 summarizes these observations.

Table 1. Logs of *Chandra* observations used in this paper.

Notation	Date	Interval (year)[a]	Exposure (ks)	Configuration[b]
First	1999 Aug 29	—	2.7	ACIS (3.2) + HETG
Second	2001 Apr 06	1.7	2.6	ACIS (0.2)
Third	2003 Jan 05	3.3	35	ACIS (0.3) + HETG

[a]Interval from the first observation.

[b]Number in parenthesis indicates the frame time in seconds.

3. Results and Discussion

In contrast with the short-term variations seen in the inner regions, the long-term variations are prominent in the outer regions, i.e., the torus and the southern jet. In the following sections, we will discuss these variations separately.

3.1. The Northeast of the Torus

Figure 1 shows expanded views of the northeast of the torus. The brightness scales of these images are normalized to the bright region of the torus, not by exposure time, because of differences in the observational configurations.

Images of the first and second epoch observations are quite similar. The bright "thick" torus is encircled by circular structures at its northeastern end. As reported previously, these two structures appear to expand between first and second epoch observations (Mori et al. 2000; Mori 2002). In contrast with the similarity between the first and second epoch images, the morphological transition from the second to the third epoch image is remarkable. The bright region of the torus appears to have shrunk and become "thin", and the circular structures have decayed into several arcs.

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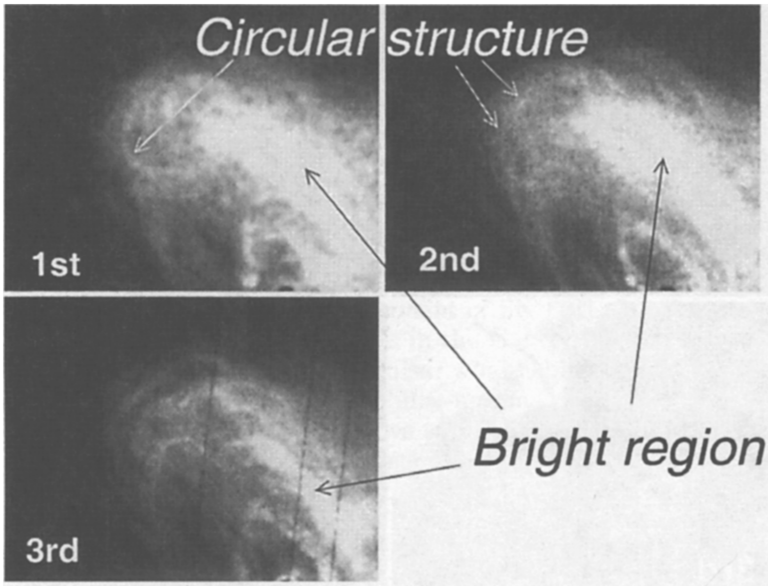

Figure 1. Expanded views around the northeast of the torus of first (top left), second (top right), and third (bottom left) epoch observations. Black lines seen in the third epoch image are instrumental effects.

Now it is clear that the torus is not steadily expanding; the overall extent is almost constant over decades, but the boundary of the torus varies with an angular scale of a few arcseconds and a time scale of years. It is as if we were seeing a top of a fountain. Greiveldinger & Aschenbach (1999) reported surface brightness variations of the Crab Nebula using *ROSAT* HRI observations spanning six years. Although *ROSAT* could not detect a morphological variation, they showed a monotonic increase of the surface brightness at the northeastern region of the torus. The brightness variation discovered by *ROSAT* is most likely related to the morphological variation discovered by *Chandra*, suggesting that the time-scale of the variation of the torus might be about a decade rather than a few years.

3.2. The Southern Jet

Figure 2 shows expanded views of the southern jet. Although the displacement of the jet is quite small, these images clearly show the growth of its overall kinked structure. The variability of the jet is reminiscent of northern variable jet of the Vela PWN (Pavlov et al. 2003). Table 2 compares the time scale of variability and the width of the Crab and Vela jets. The Crab jet is ten times larger and varies ten times more slowly than the Vela jet. If these variations are due to an MHD instability, the time-scale is proportional to the Alvén crossing time, $\tau \sim r/\nu$, where r is the width of the jet and ν is the Alven velocity (Begelman 1998). Considering that the Alvén velocity in an ultrarelativistic plasma like the Crab and Vela PWNe is more or less the same, the above equation applies to

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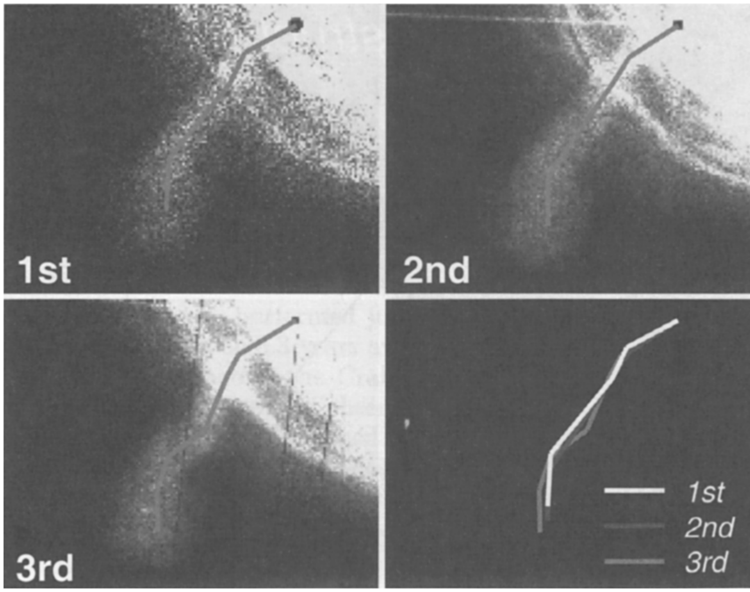

Figure 2. Expanded views of the southern jet in first (top left), second (top right), and third (bottom left) epoch observations. The line in each image traces the axis of the jet. All three lines are superimposed in the bottom right image.

both the Crab and Vela jets. Therefore, we suggest that a common mechanism is responsible for the variability of the Crab and Vela jets.

Table 2. Comparison of variable jets of the Crab and Vela PWNe.

PWN	Time scale (days)	Width (cm)
Crab	150–500	2.9×10^{17}
Vela	10–30	3×10^{16}

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