SMASHING THE GUITAR: AN EVOLVING NEUTRON STAR BOW SHOCK

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ABSTRACT

The Guitar Nebula is a spectacular example of an Hα bow shock nebula produced by the interaction of a neutron star with its environment. The radio pulsar B2224+65 is traveling at ~800–1600 km s⁻¹ (for a distance of 1–2 kpc), placing it on the high-velocity tail of the pulsar velocity distribution. Here we report time evolution in the shape of the Guitar Nebula, the first such observations for a bow shock nebula, as seen in Hα imaging with the Hubble Space Telescope. The morphology of the nebula provides no evidence for anisotropy in the pulsar wind nor for fluctuations in the pulsar wind luminosity. The nebula shows morphological changes over two epochs spaced by 7 years that imply the existence of significant gradients and inhomogeneities in the ambient interstellar medium. These observations suggest an astrophysical unique picture in situ probes of length scales between $5 \times 10^{-4}$ and 0.012 pc. Model fitting suggests that the nebula axis—and thus the three-dimensional velocity vector—lies within 20° of the plane of the sky and also jointly constrains the distance to the neutron star and the ambient density.

Subject headings: ISM: structure — pulsars: individual (PSR B2224+65) — shock waves — stars: neutron

1. INTRODUCTION

While the steady decay of spin rates observed in radio pulsars provides a good estimate of the rate of energy loss $\dot{E}$, only a small fraction of the energy output of a neutron star (NS) is typically converted to directly detectable electromagnetic radiation. Most of the spin-down energy loss is carried away by a relativistic wind, the properties of which are largely unknown. The best constraints on the relativistic wind derive from its interaction with the interstellar medium (ISM). This interaction has been observed, for example, in synchrotron nebulae such as the Crab Nebula (Kennel & Coroniti 1984; Gallant & Arons 1994; Melatos & Melrose 1996), where wisp structures are observed moving at ~0.5c (Hester et al. 2002), as well as bow shocks observed in Hα emission from shock-excited neutral gas around PSR B1957+20 (Kulkarni & Hester 1988) and various other pulsars (Chatterjee & Cordes 2002; Gaensler, Jones, & Stappers 2002).

The Guitar Nebula was discovered in deep Hα imaging observations with the 5 m Hale Telescope at Palomar Observatory (Cordes, Romani, & Lundgren 1993). Using a model for the Galactic electron density distribution (Cordes & Lazio 2002), the dispersion measure (DM = $\int n_e ds = 35.3$ pc cm⁻³) of PSR B2224+65 implies a distance of 1.9 kpc (hereafter parameterized as $D_p$). While the pulsar has a modest $\dot{E} = 10^{31.1}$ erg s⁻¹, the large space velocity of the pulsar (~1640$D_p$ km s⁻¹) provides the ram pressure needed to create a detectable bow shock nebula. The existence of an observable bow shock nebula also implies the presence of a significant neutral hydrogen component in the ISM near the pulsar. Here we describe Hubble Space Telescope (HST) observations of the time evolution of the nebula and discuss the implications of the observations for our understanding of NS relativistic winds and the ISM.

2. HST OBSERVATIONS AND MODELING

High-resolution HST observations obtained in 1994 December with the Wide Field Planetary Camera 2 (WFPC2; Holtzman et al. 1995) have been described previously (Chatterjee & Cordes 2002). New WFPC2 observations were obtained in 2001 December, with about 2.4 times the exposure time of the earlier epoch. At both epochs, exposures were combined using variable-pixel linear reconstruction (“Drizzling”; Fruchter & Hook 2002), yielding an effective pixel scale 0.0226, roughly half the size of the 0.0455 pixels on the Planetary Camera chip of the WFPC2. The Hα images at the two epochs (Fig. 1) were aligned to subpixel accuracy using eight stars (Fig. 2, left). The tip of the nebula has moved 1.75 in 7 years, consistent with the radio proper motion of PSR B2224+65 ($\mu = 182 \pm 3$ mas yr⁻¹ at a position angle 52°1 ± 0°9; Harrison, Lyne, & Anderson 1993). However, unlike the simple translation with constant shape expected for a bow shock in a uniform ambient medium, the head of the nebula has changed morphologically, showing corrugations in the limb-brightened edge as well as gaps in the Hα flux, both of which vary with time.

At the tip of the nebula, the standoff radius of the bow shock has increased over the 7 year period, as determined by model fitting (discussed below) at each epoch. Pressure balance between the relativistic NS wind and ram pressure from the ambient medium occurs at the standoff radius,

$$R_o = (E/4\pi n_s m v_s^2)^{1/2},$$  \hspace{1cm} (1)

where $n_s$ is the number density of particles with mean mass $m$ and $v_s$ is the pulsar velocity. For the Guitar Nebula, incorporating measured values for the pulsar $E$ and proper motion, the standoff radius is $R_o \approx 18D_p^{1/2}n_s^{-1/2}$ astronomical units (AU), and the predicted standoff angle is $\theta = 9.4D_p^{1/2}n_s^{-1/2}$ mas. Bright patches appear along the edges of the nebula where it is constrained, as marked with arrows in Figure 1: the location of this brightening has moved ~0.08 parallel to the pulsar motion along both sides of the nebula. However, in Figure 2 (left), the edges perpendicular to the nebula axis have moved outward by less than 0.3, remaining essentially static at several points. Meanwhile, the rear edge of Hα emission has actually moved backward by ~0.07 in 2001 compared to 1994. Possible explanations include turbulence in the shocked layers, their interaction with a complex magnetic field, or changes in any of the variables in the expression for $R_o$ (eq. [1]), including $E$. However, even...
for the largest observed glitches (Hobbs et al. 2002), $\dot{E}$ changes temporarily by $\lesssim 3\%$, a negligible variation compared to the large morphological changes observed. Besides being contrary to our general understanding of spin-down, a time-variable $\dot{E}$ also fails to explain the brightening of the nebula at the locations where it appears constricted. Indeed, it is difficult to explain the evolving morphology without invoking variations in the ambient interstellar density, although instabilities in the shock structure are also possible (e.g., Draine & McKee 1993).

We propose that the observations reflect the motion of PSR B2224+65 through random density inhomogeneities combined with a gradient toward a region of lower density. The bright rear edge ($\sim 11''$ downstream of the nebula tip in 1994) marks a sharp increase in density that the NS broke through $\sim 70$ years ago. Currently, the shock at the rear confines the relativistic NS wind, leading to a brightening of the head of the nebula and preventing the wind from powering the rest of the Guitar body, thus producing the dim, elongated, and narrow “neck” of the Guitar in Figure 1.

We argue further that the morphology of the head of the Guitar Nebula is an analog for confinement by another high-density region $\sim 300$ years ago, which created the rounded end of the Guitar body. Fluctuations in the ambient density cause the body to be brighter where it appears constricted. In a few hundred years, as the larger Guitar body fades from view, what is currently the head of the nebula may expand to become another guitar-like structure. The scenario described here, while plausible, needs to be verified with future high-resolution monitoring observations as well as time-dependent hydrodynamic modeling of shock fronts in an ambient medium with significant density fluctuations.

Currently, in order to quantify the change in standoff radius between epochs, we have modeled the shock front under the assumption that the nebula tip is in quasi-static equilibrium with the ambient medium. A momentum-conserving bow shock model (Wilkin 1996) was adapted to fit the Hα emission at each epoch. The momentum-conserving description has known limitations (Bucciantini & Bandiera 2001), especially since it applies only to an ambient medium of uniform density. To avoid these problems, we restricted the model fit to within $2\%$ of the tip of the nebula, where it is smooth and symmetric. The model is parameterized by the position angle and the inclination of the nebula to the line of sight (neither of which are expected to change significantly between epochs), the thickness of the shocked layer that emits Hα, and by a scale factor $S = D_n^{-1} n_s^{-1/2}$, which isolates the dependence of the apparent size of the nebula on distance and ambient density. Details of the model fitting procedure (for the 1994 data) are given in Chatterjee & Cordes (2002), and the best-fit parameters for both epochs (position angle, inclination, scale factor, and standoff angle) are listed in Table 1. At both epochs, the fit constrains the nebula to lie in the plane of the sky. As shown in Figure 2 (right), the best-fit scale factor varies significantly between 1994 and 2001. Since the fractional change in distance to the nebula is negligible over 7 years, the change in scale

![Image of the Guitar Nebula](image_url)

**Fig. 1.—**Hα images of the head of the Guitar Nebula. **Bottom:** Wide-field image of the Guitar Nebula obtained at the 5 m Hale Telescope at Palomar (Chatterjee & Cordes 2002). High-resolution images of the region marked with crosses in 1994 and open circles in 2001 (left). North is upward, and east is to the left. Stars are circled, and arrows mark constricted regions in the limb-brightened Hα emission that are conspicuously brighter (see text). Note that the NS is located at the very tip of the nebula at each epoch.

![Image of the Guitar Nebula](image_url)

**Fig. 2.—**Left: Outline of the limb-brightened head of the Guitar Nebula in 1994 (filled circles) and 2001 (open circles), obtained by eye. The images are aligned using eight bright stars in the PC image at each epoch: to demonstrate the image registration, two stars in the PC image section displayed in Fig. 1 are marked with crosses in 1994 and open circles in 2001. Right: Slices through the best-fit point on the $\chi^2$ surface for the model fit procedure on 1994 data (filled circles) and 2001 data (open circles), showing the relative change in $\chi^2$ as a function of the scale factor $S = D_n^{-1} n_s^{-1/2}$. The implied change in ambient density at the nebula tip is $n_s(2001)/n_s(1994) \approx 0.7$. 
factor implies a decrease in ambient density by a factor of \( \sim 0.7 \) (from 0.006 to 0.004 cm\(^{-3}\)) for \( D = 1.9 \) kpc over 1.3, corresponding to a length scale of 2500D\(_{1.9}\) AU. The implied change in DM for density changes on this length scale is \( \sim 10^{-4}\) pc cm\(^{-3}\), which may be detectable with sensitive pulse timing observations. In addition, the fits establish a joint constraint on the distance to the NS and the ambient density, \( D_{\text{ns}} = 0.48n_{\text{e}}^{-1/4} \). We note that the densities obtained above are low, suggesting a possible overestimate of the distance. For an ambient density of 0.05 cm\(^{-3}\), which is comparable to the density of the local warm ionized medium (e.g., Paresce 1984), the implied distance is 1 kpc (and the height above the Galactic plane is reduced from 240 to 120 pc).

To check for unresolved small-scale structure in the limb-brightened nebula, the autocorrelation function was calculated for sections of the image with and without nebular emission. After accounting for Poisson noise and the contribution from smooth extended structure, the excess in the on-nebula autocorrelation function due to barely resolved or unresolved structure (50 mas or less) is less than 5% of the larger scale nebular emission. We conclude that 50 mas represents a lower limit on the angular scale of structure in the ISM probed by these HST observations of the Guitar Nebula.

3. DISCUSSION

The wavenumber spectrum for electron density fluctuations in the general ISM has been delineated through a variety of measurements, including radio scintillation, scattering, pulse time of arrival, and Faraday rotation, as illustrated in Figure 3. These measurements constrain the power levels in different wavenumber intervals and suggest an overall consistency with a Kolmogorov turbulence process (Armstrong, Rickett, & Spangler 1995), although this consistency is only coarse and may be an illusion associated with the large-amplitude scale of the diagram. Departures from the Kolmogorov spectrum are also inferred from pulsar scintillation measurements. The HST measurements of the Guitar Nebula provide constraints on wavenumbers not easily accessible by other probes and therefore provide a new tool for investigating fine structure in the interstellar density.

Along with the properties of the ISM, the Guitar Nebula also provides a probe of the pulsar’s relativistic wind. The properties of pulsar winds, including the magnetization parameter \( \sigma \), the ratio of the Poynting flux to the kinetic energy flux, have been inferred primarily from the Crab Nebula (Kennel & Coroniti 1984; Gallant & Arons 1994; Melatos & Melrose 1996). The existence of bow shock nebulae such as the Guitar requires collisional excitation of the neutral ISM through interactions with shocked electrons and protons. These charged particles can be ejected from the NS itself or originate from interstellar atoms through photoionization or magnetic reconnection outside the pulsar light-cylinder radius \( R_{\text{LC}} = cP/2\pi \). The process by which the NS Poynting flux is converted to particle kinetic energy is not well understood: over-

views of different processes are provided by Begelman & Li (1992), Gallant et al. (2002; ion loading), and Lyubarsky & Kirk (2001; striped pulsar winds). At the standoff radius \( (R_{\text{p}} \gg R_{\text{LC}}) \), pressure balance requires that the spin-down energy of the NS be carried by the particle flux \( (\sigma \ll 1) \), but the shape of the nebula may encode information about the (rotation-averaged) shape of the NS wind.

Along with the Guitar Nebula, future observations of the evolution of bow shock nebulae will be possible for the nearby radio-quiet NS RX J1856.5−3754 (van Kerkwijk & Kulkarni 2001), only \( \sim 120 \) pc away (Kaplan, van Kerkwijk, & Anderson 2002; Walter & Lattimer 2002). Even at its relatively low speed \( (<200 \text{ km s}^{-1}) \), the NS travels \( \sim 1\)" in a year, and evolution of the nebula should be evident on roughly this timescale. PSR J2124−3358, a nearby millisecond pulsar with a complex bow shock nebula (Gaensler et al. 2002), is also promising in this regard, while the discovery of a bow shock nebula powered by the Poynting flux from a magnetar would allow investigation of the relativistic wind in the presence of an ultrastrong magnetic field.

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