RECONSTRUCTING THE GUITAR: BLOWING BUBBLES WITH A PULSAR BOW SHOCK BACKFLOW

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ABSTRACT

The Guitar Nebula is an Hα nebula produced by the interaction of the relativistic wind of a very fast pulsar, PSR B2224+65, with the interstellar medium. It consists of a ram-pressure confined bow shock near its head and a series of semicircular bubbles further behind, the two largest of which form the body of the Guitar. We present a scenario in which this peculiar morphology is due to instabilities in the backflow from the pulsar bow shock. From simulations, these backflows appear similar to jets and their kinetic energy is a large fraction of the total energy in the pulsar’s relativistic wind. We suggest that, like jets, these flows become unstable some distance downstream, leading to rapid dissipation of the kinetic energy into heat, and the formation of an expanding bubble. We show that in this scenario the sizes, velocities, and surface brightnesses of the bubbles depend mostly on observables, and that they match roughly what is seen for the Guitar. Similar instabilities may account for features seen in other bow shocks.

Subject headings: instabilities — ISM: bubbles — ISM: individual (Guitar Nebula) — ISM: jets and outflows — pulsars: individual (PSR B2224+65)

1. INTRODUCTION

Many pulsars travel at high speed, and the collision between their relativistic winds and the interstellar medium leads to the formation of bow shocks. These shocks are observed most readily at X-ray and optical wavelengths: the shocked relativistic wind will emit mostly synchrotron radiation, while the shocked interstellar medium will emit—if it is partially neutral—copious Hα emission (for a review, see Gaensler & Slane 2006).

Arguably the most spectacular bow shock is the Guitar Nebula, made by one of the fastest pulsars known, PSR B2224+65 (Cordes et al. 1993). This Hα nebula has, as the name implies, a guitar-like shape, with a bright head, a faint neck, and a body consisting of two larger bubbles (see Fig. 1). Cordes et al. (1993) suggest this morphology might reflect variations in either the pulsar energy injection rate or the interstellar medium density.

In this Letter, we investigate whether instead the peculiar morphology could be due to instabilities in the jetlike flow of pulsar effluvium away from the bow shock. Fast backflows are a natural consequence of bow shocks: the pulsar wind is greatly heated at the shock, which, for the usual case where cooling is slow, leads to a high pressure that drives a flow in the only direction available, to the back. From simulations (e.g., Bucciantini et al. 2005), the flows seem similar to jets, being well-collimated and fast, and seem to carry most of the pulsar wind energy. Jetlike flows are indeed seen in X-ray observations, which also show that only a small fraction of the energy is radiated (for a review, Kargaltsev & Pavlov 2008).

So far, the simulations have not extended far to the back, but if the backflow is similar to a jet, one might expect it to become unstable farther downstream. From simulations of jets (e.g., Bodo et al. 1998), this instability would lead to mixing with the ambient medium and rapid dissipation of the kinetic energy into heat. The simulations have not followed what happens beyond this initial mixing, but it seems plausible that the material would expand rapidly and drive a bubble. If so, it might initially expand faster than the pulsar motion, and gain further energy from the jet. With time, however, it will slow down, and once the pulsar has moved sufficiently far ahead, the jet will become so long that it becomes unstable before reaching the bubble, and a new bubble will be formed. We suggest the body of the guitar is made up of two such bubbles, while another one has just started to form near the head.

In § 2 we describe our model in more detail, and in § 3 we compare it with the properties of the Guitar Nebula, finding qualitative agreement. In § 4 we discuss implications as well as ways in which our model could be tested.

2. BLOWING BUBBLES WITH A BOW SHOCK BACKFLOW

We consider a pulsar that loses energy at a rate $\dot{E}$ in the form of a relativistic wind and moves at velocity $v_\inj$ through a medium of density $\rho_\inj$. The resulting bow shock will have a standoff distance $r_0$ given by

$$\frac{\dot{E}}{4\pi r_0^2 c} = \rho_\inj v_\inj^2. \quad (1)$$

The bow shock leads to a jetlike backflow carrying kinetic energy at a rate $f_\strel E_\inj$, where from simulations the efficiency factor $f_\strel$ is close to unity (Bucciantini 2002). We assume the backflow will become unstable some distance $l$ behind the neutron star, rapidly mix with shocked ambient medium, and dissipate its energy, leading to the formation of a bubble. Assuming also that the bubble is fed more energy for some time $t_\inj$, and expands adiabatically for a total time $t_\exp$, the bubble radius will be approximately given by the Sedov-Taylor solution,

$$R_\strel = \frac{\eta_s (f_\strel E_\inj l_{\text{los}})}{f_\strel \rho_\inj} t_\exp^{1/5} \frac{1}{\dot{E}^{1/5}} \quad (2)$$

where $\eta_s$ is a dimensionless constant of order unity that depends on the adiabatic index of the interstellar medium and the extent to which energy injection is instantaneous (see below), and $f_\strel$ takes account of possible variations in density between the head of the bow shock and the location of the bubble (for our model, by assumption, $f_\strel \approx 1$).

Equations (1) and (2) both depend on the ratio $\dot{E}/\rho_\inj$, suggesting the bubble radii can be expressed in terms of bow shock
pulsar. Observationally, it is easiest to measure surface bright-
becomes unstable; and that the instability drives a bubble that
three main premises are that the backflow is jetlike; that it
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For a bow shock, this implies\(^4\) for relativistic jets in a 10 times denser medium, Hardee et al.
length scales about 10 times the jet radius. For instance,
perturbations appear to grow on
d

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\(\dot{E} = \frac{4\pi c}{\rho_o} \frac{d'm^2_i}{d^i} \theta_i^2\), (3)

where \(i\) is the inclination, \(d\) the distance, \(\mu = v_i \sin i d/d\) the proper motion, and \(\theta_i = f_i r_i d/ld\) the angular standoff distance (\(f_i\) is a function of the inclination, with \(f_{iso} = 1\), but \(f_i \neq \sin i\); see Gaensler et al. 2002). We also write \(t_{exp} = (\alpha - \lambda)/\mu_s\), where \(\alpha\) is the angular separation between the center of the bubble and the pulsar and \(\lambda = l \sin i d/l d\) the angular size corresponding to the instability length \(l\), and \(t_{iso} = (\beta - \Delta\lambda)/\mu_s\), where \(\beta\) is the separation between the center of the bubble and the next one closer to the pulsar, and \(\Delta\lambda\) takes into account that two bubbles can have formed at slightly different distances behind the pulsar. Note that for the bubble closest to the pulsar, \(t_{iso} = t_{exp}\) and one should replace \(\beta - \Delta\lambda\) with \(\alpha - \lambda\) below. With this, the angular radius of a bubble, \(\theta_b = R_b/ld\), is given by

\[\theta_b = f_b \left(\frac{4\pi c}{v_s}\right)^{1/5} |\theta_0^{*}(\alpha - \lambda)^{2/5} (\beta - \Delta\lambda)|^{1/5},\] (4)

where \(f_b = \eta_i (f_{jff}/f_i^3 \sin i d/ i d)^{1/5}\) is of order unity. One sees that for a bubble far behind the pulsar (i.e., \(\lambda \ll \alpha\) and \(\Delta\lambda \ll \beta\)), there is little room to fiddle: the uncertainties in the efficiency factors, geometry, and velocity may amount to a factor 2, but they enter only to low power.

With the sizes, the expected H\(\alpha\) photon rates are given by

\[n_{\alpha,b} = \frac{f_a 4\pi R_b^2 v_s n_{H\alpha}}{4\pi d^2} = f_a n_{H\alpha} \theta_i^2 \mu_s d,\] (5)

where \(f_a\) is the number of H\(\alpha\) photons emitted per neutral particle before that particle is ionized (\(-0.05 and 0.27 for case A and B, resp., weakly dependent on velocity; Chevalier & Raymond 1978), \(n_{H\alpha}\), the neutral hydrogen number density, \(v_s\) the expansion rate, and \(\mu_s\) the corresponding proper motion,

\[\mu_s = \frac{2}{5} \mu_s \frac{\theta_b}{\alpha - \lambda},\] (6)

where the coefficient becomes 3/5 for the bubble closest to the pulsar. Observationally, it is easiest to measure surface brightnesses near the limbs of bubbles. For measurement length scales \(\delta \ll \theta_o\), one predicts \(s_{limb} \sim n_{H\alpha}(1/2 \pi \theta_o^2) (2\theta_o/\psi) \sim \mu_s \theta_o^{10/3}\).

We now discuss our assumptions and simplifications. Our three main premises are that the backflow is jetlike; that it becomes unstable; and that the instability drives a bubble that is fed further energy for some time. The first two are supported by simulations: bow shocks appear to give jetlike backflows with \(r_{exp} = 4R_b\) (Bucciantini et al. 2005), and jets do seem to become unstable (with much of the recent work focusing on how to prevent this from happening too quickly; for a review, e.g., Hardee 2004). Typically, perturbations appear to grow on length scales \(l_{ij}\) about 10 times the jet radius \(r_{inj}\). For instance, for relativistic jets in a 10 times denser medium, Hardee et al. (1998) found \(4 \leq l_{ij}/r_{exp} \leq 15\). For a bow shock, this implies angular growth length scales \(\lambda\), in the range \(16 \leq (\lambda r_{inj}/\theta_o)/(f_i \sin i) \leq 60\). Of course, instability will only occur after a few growth times, so the angular distance \(\lambda\) should be correspondingly larger. We will see in \(\S\) 3 that this is consistent with the Guitar Nebula. It also validates an implicit assumption we made, that the bubbles do not overtake the pulsar, i.e., that \(\alpha > \theta_o\) at all times. From equation (4), the minimum value of \(\alpha - \theta_o\) occurs at \(\alpha = \lambda + \theta_o(3f_i/5)^{1/2}(4\pi c/n_{H\alpha})^{1/2}\); this becomes negative only for \(v_s \approx 50 f_b (50\theta_o/\lambda) \text{ cm s}^{-1}\), much smaller than the velocity of PSR B2224+65.

What is not clear yet, however, is whether jet instabilities could lead to bubbles, and, if so, whether our simplified description is justified. In particular, in using the Sedov-Taylor solution, we assume energy is injected (nearly) instantaneously at a single point in a homogeneous medium, and that the expansion is adiabatic. Of these assumptions, the last is reasonable: the cooling time, \(t_{cool} \approx 20,000 \text{ yr} (v_s/100 \text{ km s}^{-1})^4 (\rho_v/10^{-23} \text{ g cm}^{-3})^{-1}\) (Koo & McKee 1992), is much longer than the \(\sim 300\) yr it takes PSR B2224+65 to cross the nebula (here, we scaled to the lowest velocities and highest densities appropriate for the Guitar Nebula). The others are less realistic: energy will be injected some time in a larger, not necessarily spherical volume embedded in a medium which, close to the axis, has been through the bow shock. Injection over some time should lead to a bubble that initially expands somewhat more slowly. Indeed, Dokuchaev (2002) found that for continuous energy injection, equation (2) can be used, but with a somewhat smaller value of \(\eta_i\) (e.g., \(\eta_{Sedov} = 0.929\) for \(t_{exp} = t_{iso}\) instead of \(\eta_{Sedov} = 1.152\) for \(t_{iso} \ll t_{exp}\)). This may be counteracted, however, by the initial expansion being in preshocked, less dense medium. At later times, our estimates should depend less on these initial conditions, but rather on the extent to which bubbles can be treated in isolation, when in the Guitar Nebula they appear to have merged (Fig. 1). Overall, we conclude that our heuristic model will only be good at the factor 2 level.

3. RECONSTRUCTING THE GUITAR

To see how well our model applies to the Guitar Nebula, we retrieved a deep H\(\alpha\) image taken on 2000 December 6 for the Chamaeleon survey (Zhao et al. 2005), and measured properties of what seemed the three most obvious bubbles (see Fig. 1 and Table 1): the two forming the body of the guitar, and one just behind the pulsar (hereafter, bottom, middle, and head). For all bubbles, the estimates of the angular separation from the pulsar, \(\alpha\), and of the angular radius, \(\theta_o\), are quite reliable, but for the middle bubble, the separation to the next closest bubble, \(\beta\), is relatively poorly defined, since there may be an additional bubble in the neck.

For our estimates, we also need the standoff distance \(\theta_o\). Chatterjee & Cordes (2004) find that the shape of the bow shock—as seen in H\(\alpha\) images taken with the Hubble Space Telescope (HST)—is reproduced well with the analytic model of Wilkin (1996). For data sets taken in 1994 and 2001, they infer inclinations \(i \approx 90^\circ\) and standoff radii \(\theta_o \approx 0.12^\circ \pm 0.04^\circ\) and \(0.15^\circ \pm 0.04^\circ\), respectively. Since H\(\alpha\) is emitted outside the actual standoff distances, with \(\theta_o = 1.5\theta_b\) (Bucciantini 2002), one infers \(\theta_o = 0.09^\circ\), which we will use below. We will also use the observed proper motion of \(\mu_s = 0.182^\circ\) yr\(^{-1}\) (Harrison et al. 1993) and scale the pulsar speed to \(v_s \approx 1500 \text{ km s}^{-1}\) (where we used \(i = 90^\circ\) and a distance \(d = 1.8\) kpc, as implied by the dispersion measure of 35.30 pc cm\(^{-3}\) and the NE2001 electron density model of Cordes & Lazio 2002).

3.1. Sizes

In matching our model to the measurements, we first note that the existence of the head bubble implies \(\lambda < 9^\circ\). Thus, for
the bottom bubble, $\lambda \ll \alpha$ and $\Delta \lambda \leq \lambda \ll \beta$. For this case, equation (4) simplifies to $\theta_s = f_v \sqrt{[4 \pi c/v_s] \alpha^2 \beta} = 18.3'' f_v$; to match the observed radius of 16'' thus requires $f_v = 0.9$, close to unity as expected.

Using this value of $f_v$ for the head bubble, we find we require $\lambda \approx 7.5''$ to match the observed small size of 2''. This implies $\lambda/\theta_0 = 80$, in line with expectations (§ 2). It also implies the bubble formed only recently, about $(\alpha - \lambda)/\mu, = 8$ yr before the image was taken. We return to this below.

For the middle bubble, we find that to match its observed size requires $\beta - \Delta \lambda \approx 5.5''$. This is much smaller than for the bottom bubble, since to produce this relatively small bubble requires much less energy. It raises the question, however, what happened to the energy dissipated later, outside the middle bubble. One possibility is that more energy was injected in the middle bubble, but that as it grew, it merged and equilibrated with the larger bottom bubble. If so, our above estimate of $f_v$ would be too large. Clearly, we have reached the limits of applicability of our simplistic picture of individual, spherical bubbles.

3.2. Proper Motions and Brightnesses

Our model predicts expansion rates (see Table 1). For the head bubble, the predicted rate is fast, $\sim 0.15''$ yr$^{-1}$. By comparing HST images, Chatterjee & Cordes (2004) indeed find that the head bubble expanded between 1994 and 2001, especially to the back, at a rate comparable if slightly slower than that predicted, of $\sim 0.10''$ yr$^{-1}$. Interestingly, the bubble also became brighter, consistent with the idea that it formed only recently. This evolution is confirmed by inspection of unpublished HST data taken in 2006. Furthermore, the head bubble is dimmer in the 1992 discovery image of Cordes et al. (1993) than it is in Figure 1 or in the 1995 image shown by Chatterjee & Cordes (2002).

For the middle and bottom bubbles, the predicted expansion rates are slower, $\sim 0.02''$ yr$^{-1}$. This is difficult to detect from the ground. It may be detectable over the 12 years spanned by the HST images, but given the low signal-to-noise ratio, this will require detailed modeling, which we have not attempted.

The lower proper motions for the middle and bottom bubbles also imply predicted limb surface brightnesses about 3 times fainter than for the head bubble. This is roughly consistent with the observed ratio of 4 (Table 1).

4. RAMIFICATIONS

We found that we could roughly reproduce the Guitar Nebula assuming the jetlike backflow from the pulsar bow shock becomes unstable and dissipates rapidly, causing expanding bubbles. If this were to happen generally, one might expect other sources with jets or bow shocks to show Guitar-like bubbles,
yet none appear to be known. For jet sources, this may not be surprising: many jets are denser than the medium they move through, and hence more stable, and disruptions that do occur may be difficult to distinguish from, e.g., changes in jet orientation.

For other bow shocks, the absence of bubbles may partly be a selection effect: most have much larger standoff radii than the Guitar, and hence any bubbles would be at correspondingly larger distances, where they might be missed, especially as they would be fainter than the bow shock (or even invisible if the expansion velocity became too low or if radiative effects became important; both perhaps relevant especially for stellar wind bow shocks). The one possible exception is PSR B0740−28, which has a Hα bow shock with a relatively small standoff radius of $\theta_s = 1.0^{\circ}$ as well as "shoulders" farther behind (Jones et al. 2002). If related to an instability, one infers observations match expectations better. For PSR J1509−5850, a kink at $\theta_s = 0.75^{\circ}$, shows a bulbous structure $\sim 1.5^{\prime}$ behind the pulsar (the "puff"), but also a smooth, straight tail of $\sim 3^{\prime}$, without a clear kink at $\theta_s = 0.5^{\circ}$, the X-ray tail extends for $\sim 5.6^{\prime}$ and shows clear structure, with a change in brightness at $1.3^{\prime}$, a kink at $3^{\prime}$, and a bright radio spot coincident with its end point (Hui & Becker 2007a; Kargaltsev et al. 2008). Comparing with the large bubbles in the Guitar, the typical length scale of $\sim 1.5^{\prime}$ for the knots and kinks is about a factor 3 larger, roughly consistent with the ratio of the standoff distances. For PSR B1929+10, with $\theta_s = 2.3^{\circ}$, the tail extends up to $10^{\prime}$ and again shows substantial structure, with brightenings at $\sim 2^{\prime}$ and $\sim 5^{\prime}$, the latter coincident with a radio feature (Becker et al. 2006; Misanovic et al. 2007). Again scaling with the standoff radii, the $5^{\prime}$ feature could be similar to the head bubble in the Guitar.

Overall, we conclude that our model of instabilities in a bow shock backflow roughly reproduces observations of the Guitar Nebula, without the need to appeal to variations in the density of the ambient medium, nor to energy sources beyond what is expected to be carried by the backflow. It also seems consistent with what is seen in other pulsar bow shocks. The model could be tested further both with observations and simulations. Observationally, one test would be to measure the expansion velocities in the Guitar bubbles, either by determining proper motions, or by spectroscopy (from the broad component of the Hα profile, as done for nonradiative shocks in supernova remnants; Raymond 1991). Given the observed Hα surface brightness, this would allow one to estimate the ambient density, which should be similar to that at the location of the bow shock in our model, but substantially lower if the bubbles reflect density variations (Cordes et al. 1993; Chatterjee & Cordes 2004).

Simulations of bow shocks that extend to larger scales might show whether instabilities in fact lead to bubbles or rather to more continuous structure, or whether perhaps the process is sufficiently stochastic that both can occur (possibly leading to a shape like the Guitar’s neck). If bubbles form, the simulations might also shed light on details of the morphology, such as the closed appearance at the back of the head and bottom bubbles.

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