PULSAR BOW SHOCKS AS PROBES OF WARM NEUTRAL GAS

Bryan M. Gaensler,[1] Benjamin Stappers,[2,3] Shami Chatterjee,[4,5] Parviz Ghavamian,[6] D. Heath Jones,[7] & James Cordes[4]

[1]*Harvard-Smithsonian Center for Astrophysics* [2]*ASTRON* [3]*U Amsterdam* [4]*Cornell University* [5]*NRAO* [6]*Rutgers University* [7]*ANU*

Abstract   Pulsars have mean space velocities $\gtrsim 500$ km s^{-1}. The consequent ram pressure results in tight confinement of the star's energetic wind, driving a bow shock into the surrounding medium. Pulsar bow shocks have long been regarded as a curiosity, but new optical and X-ray observations are both rapidly expanding the sample of such sources, and are offering new ways to probe the interaction between pulsars and their environments. Here we discuss some of these new results, and explain how these data can be used to probe the density and structure of neutral gas in the interstellar medium.

1.   Introduction

Pulsars release their rotational kinetic energy via relativistic winds, with "spin-down luminosities" typically in the range $\dot{E} = 10^{32} - 10^{38}$ ergs s^{-1}. Pulsars also have high space velocities, typically $V_{PSR} = 100 - 2000$ km s^{-1}, meaning that they are almost always moving supersonically through surrounding gas. We can therefore conclude that most pulsars drive bow shocks in the ambient interstellar medium (ISM).

Pulsar bow shocks are potentially a very powerful probe of interstellar gas. The precision of pulsar timing means that we usually have very accurate measurements of a pulsar's $\dot{E}$, its position, its proper motion, and its distance (via either parallax or the dispersion of the pulses). Thus in a pulsar bow shock, the only remaining unknowns are the density/structure of the ISM, plus the inclination of the pulsar's velocity vector to the line of sight. Furthermore, pulsars typically have ages of $10^6 - 10^9$ years, so that they are usually well-removed from star-forming regions and are thus a relatively unbiased tracer of the ISM.

2. Pulsar Bow Shocks: Theory and Observation

The pulsar/ISM interaction generates two shocks, a forward shock (the bow shock) and a reverse shock (the pulsar wind termination shock), separated by a contact discontinuity. The fundamental size scale of the system is the distance along the symmetry axis between the pulsar and the contact discontinuity. This "stand-off distance", r_w, is set by ram-pressure balance: $\dot{E}/\Omega r_w^2 c = \rho V_{PSR}^2$. Here Ω is the solid angle of the outflow in the pulsar wind, and ρ is the ambient density. The shape of the bow shock surface has an analytic solution, as shown by [1].

We observe two distinct types of emission from bow shocks. The forward shock is often seen in Hα, resulting from collisional excitation of neutral hydrogen, plus charge exchange with protons behind the shock. We also see radio/X-ray synchrotron emission, produced by relativistic particles accelerated at the termination shock. Only around PSR B1957+20 (Fig 1, left) have we as yet seen both Hα and synchrotron emission in the same source [2].

3. Size and Morphology

The value of r_w can be directly estimated from an image of a bow shock. If we assume that $\Omega \approx 4\pi$, and derive $\dot{E}$ and V_{PSR} from pulsar timing and dispersion, we can use pressure balance to determine ρ. This calculation is complicated by the unknown inclination angle and other effects, but overall, it can be shown that the known bow shocks are all consistent with ambient densities $n_0 \approx 0.1$ cm^{-3}, as expected for the warm neutral ISM [3].

The morphology of the bow shock powered by PSR J0437–4715 is well described by the idealised form derived by [1], allowing one to derive the inclination angle of the pulsar's velocity vector to the line of sight [4]. However, the recently discovered bow shocks around PSRs J2124–358 [5] and B0740–28 [6] show asymmetries, kinks and other features in their Hα emission (Fig 1, centre & right). These deviations from the analytic solution can be used to infer the presence of a density gradient and/or relative flow velocity in the ambient ISM [5, 7].

4. Time Variability

A pulsar moving at 500 km s^{-1} at a distance of 1 kpc has a proper motion of 100 mas year^{-1}. The resulting bow shock motion is easily detectable in a few years with modern optical facilities. For example, if a pulsar is moving into a region of increasing density, one expects the head to narrow and the stand-off distance to shrink. This is indeed what has been observed in the "Guitar Nebula" powered by PSR B2224+65, between two epochs separated by 7 years [3]. Such changes suggest fluctuations at the level of $\Delta n_0 \sim 1 - 10$ cm^{-3} on

Figure 1.   Pulsar bow shocks. In each case, the white arrow indicates the pulsar's projected direction of motion. **Left:** Hα (grayscale) and X-ray (contours) emission around PSR B1957+20 [2]; **Centre:** Hα emission around PSR J2124–3358 [5]; **Right:** Hα emission around PSR B0740–28 [6].

scales $\Delta x \sim 0.02$ pc. Further such measurements of density variations may may provide a useful "missing link" between the density fluctuations seen in H I at scales $\sim 0.1 - 200$ pc (e.g. [8]) and the "tiny scale atomic structure" at scales $\sim$5–100 AU seen toward pulsars and through VLBI (e.g. [9]).

5.   Conclusions

We are now planning a number of further avenues of investigation: multi-epoch imaging to better characterise the time-variability of these sources; deep spectroscopy to identify high-velocity Hα emission and thus probe the post-shock flow; modelling of variations in brightness and thickness seen around the shock; searching for UV lines from bow shocks to probe pulsars embedded in ionised gas; modelling of X-ray and radio data from shocked pulsar winds; and deeper optical searches with Magellan to increase the sample beyond the six optical bow shocks currently known. It is important to realise that the number of promising targets to search is rapidly increasing — the number of known pulsars has doubled in the last five years, and probably will do so again in another five years. While we are only just beginning to explore their potential, all these considerations argue that pulsar bow shocks are emerging as an exciting new probe of the ISM.

Acknowledgments

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6.   Discussion

Hester: We have tried to find Hα from pulsar bow shocks in the past. Good luck!

Gaensler: The work done in the mid-1980s was carried out with the Palomar $60''$, using a 15-Å filter and $1''\!.2$ pixels. Our new observations are with a 6.5-metre telescope, a 7-Å filter and $0''\!.07$ pixels. We thus expect to be $\gtrsim 10$ times more sensitive than previous searches. Indeed one of our recently discovered bow shocks, PSR B0740–28 [6], was a Palomar non-detection.

Benjamin: How many of the pulsars in the current sample have parallaxes, and can you associate these with neutral clouds?

Gaensler: Two bow shock systems have parallaxes: PSR J0437–4715 and RX J18576.5–3754. These are both nearby (< 200 pc), so it is difficult to separate any associated H I clouds from local gas.

Raymond: The X-ray trail behind PSR B1957+20 is surprisingly narrow. Why?

Gaensler: This was a surprise to us also; simulations suggest that this region should be reasonably broad. We see this narrow tail behind other objects also, e.g. PSRs B1757–24 ("the Duck") and J1747–2958 ("the Mouse"). This may represent a nozzle effect or be the result of magnetic collimation.

Slavin: Doesn't the analytic expression for the bow-shock shape assume that the gas has radiatively cooled?

Gaensler: Yes. However, simulations show that the head of a pulsar bow shock still has a shape which is a good match to the analytic expression [10, 11]. There are deviations from the analytic solution in the tail region, however.

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