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Pulsar Bow-Shocks

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Abstract. The study of pulsar bow-shocks is one of the most promising ways towards the understanding of the interactions between neutron stars relativistic winds and their environment. These objects are best resolved as Hα nebulae but velocity-driven features are seen also in the X–ray and radio bands. We present a preliminary multiwavelength catalogue of pulsar bow-shocks.

Key words. pulsars – relativistic winds – HII regions

1. Pulsar Wind Nebulae

Most of the spin-down energy of a pulsar ($\dot{E}_{rot}$ =10^{35}-10^{39} erg/s for youngest sources) is expelled in its surrounding in the form of a relativistic ($\gamma \sim 10^6$) magnetized wind. When the pulsar wind is confined by an external pressure (M), a shock might occur at the equilibrium distance (R_{SO}) between the wind pressure and M:

$$\frac{\dot{E}_{\rm rot}}{4\pi {R_{SO}}^2 c} = M$$

At this termination shock, particles are accelerated and synchrotron radiation is emitted up to X-ray energies. A Pulsar Wind Nebula (PWN) becomes then observable, representing a sort of calorimeter for the energy emitted by the neutron star.

There are different types of PWNe depending mainly on the origin and strength of the external pressure M.

Static PWNe or plerions (e.g. Crab nebula) could originate from supernova cold ejecta inside the SNR shell interacting with the overpressurized pulsar wind; "binary" PWNe (e.g. PSR J0737-3039) could result from the interaction between the winds of two orbiting stars; "bow-shock" PWNe (e.g. Black Widow) for which M is the ram pressure originating from the supersonic motion of the pulsar interacting with the interstellar medium (ISM). In this case, M=ρV^2 where ρ is the ISM density and V is the pulsar velocity. For typical pulsar velocities of ~100 km/s and ISM density of ~1 cm^{-3}, the resulting ram pressure is $M \sim 10^{-10} g/(s^2 cm)$ and the stand-off distance is R_{SO}~10^{16}-10^{17}cm, that means structures resolved at few arcsec (for d~1 kpc) from the NS (Wilkin 1996; Bucciantini 2002). Pulsar bow-shocks can be observed through excitation lines of ISM atomic hydrogen (Hα line) or by synchrotron emission by wind particles in the magnetic field compressed by the shock that is typically of the order of 10^{-4}-10^{-5} Gauss. Pulsar Bow-Shocks are faint (L=10^{-5}-$10^{-3}\dot{E}_{rot}$), but in principle they are common phenomena (they require PSR velocities of only a few 10 km/s for their formation) and therefore represent an interesting challenge for future high-energy telescopes aimed to detect their synchrotron emission. The study of pulsar

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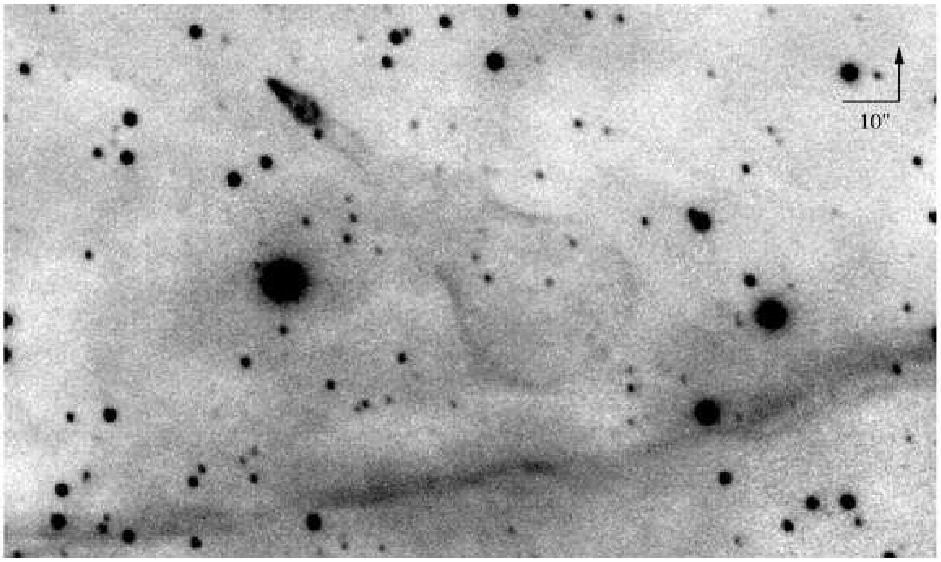

Fig. 1. The Guitar Nebula: an example of Hα bow-shock with "cometary" shape due to the supersonic motion (>1000 km/s) of the radio pulsar B2224+65 with direction close to the plane of sky (Chatterjee & Cordes, 2002).

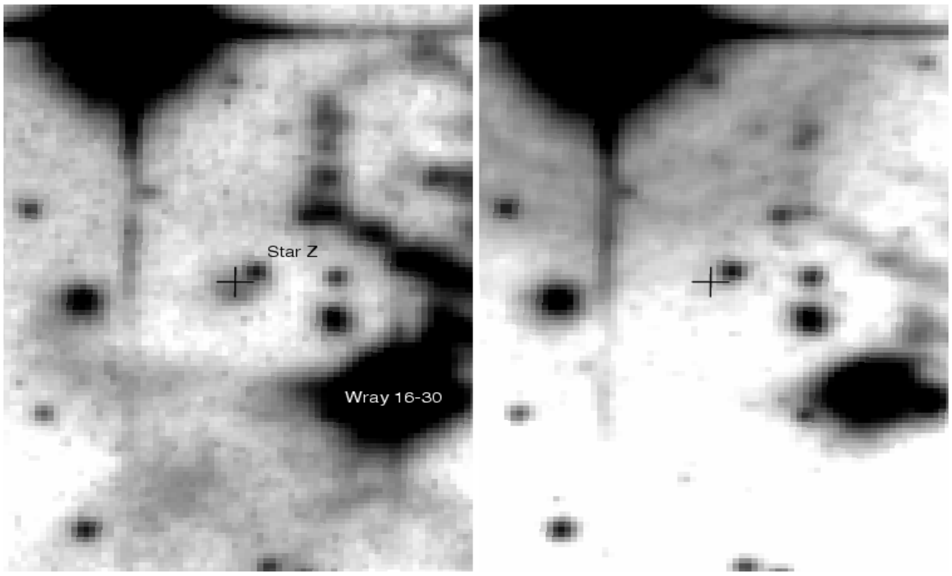

Fig. 2. Hα (left) and R band (right) images of the central region of SNR G266.2-1.2. The cross indicates the position of the neutron star AX J0851.9-4617.4. The roughly circular nebula of 6" only visible in the Hα filter is coincident with the position of the X-ray source. It represents an example of "bullet" bow-shock (NS motion close to the line of sight and/or low velocity; Pellizzoni et al. 2002)

Table 1. Preliminary catalogue of firmly identified (upper panel) and candidate (lower panel) pulsar bow-shocks.

Name	Hα, X, radio	type	d kpc	$log(\dot{E}_{rot})$ erg/s	V km/s	$ref.$
PSR J0437-4715	H - -	ms	0.14	34.1	180	1,2
CXOU J061705.3+222127 (IC443)	- X R	ns	1.5	-	250	3
PSR B1757-24 (”Duck”)	- X R	psr	5.0	36.4	<590	4
PSR B1853+01 (W44)	- X R	psr	2.6	35.6	370	5
PSR J1747-2958 (”Mouse”)	- X R	psr	5.0	36.4	180	6
J1856.5-3754	H - -	ns	0.14	-	240	7,8
PSR B1957+20 (”Black Widow”)	H X -	ms	1.5	35.0	220	9
PSR B0740-28	H - -	psr	1.9	35.2	220	10
PSR J2124-3358	H - -	psr	0.27	33.6	100	11
PSR B2224+65 (”Guitar Nebula”)	H X? -	psr	2.0	33.1	2500	12,13
PSR B1951+32 (CTB80)	- X R	psr	2.5	36.6	300	14
PSR J0633+1746 (Geminga)	- X -	psr	0.16	34.5	120	15
PSR J0537-6910 (N157B)	- X R	psr	50	38.7	600	16
PSR B1929+10	- X? -	psr	0.33	33.6	160	17
PSR B1643-43 (G341.2+0.9)	- - R	psr	6.9	35.6	470	18
AXJ0851.9-4617.4 (”Bullet”)	H - -	ns	<2	-	-	19
PSR J1016-5857	- X R	psr	3?	36.4	-	20
GeVJ1809-2327	- X ?	ns	1.8	-	-	21
PSR B1823-13	- X? -	psr	4.1	36.5	-	22
G0.13-0.11	- X R	ns	-	-	-	23

References. (1) Bell et al. (1995); (2) van Straten et al. (2001); (3) Olbert et al. (2001); (4) Kaspi et al. (2001); (5) Petre, Kuntz & Shelton (2002); (6) Gaensler et al. (2003a); (7) Kaplan et al. (2002); (8) van Kerkwiijk & Kulkarni (2001); (9) Stappers et al. (2003); (10) Jones et al. (2002); (11) Gaensler et al. (2002); (12) Chatterjee & Cordes, (2004); (13) Wong et al. (2002); (14) Safi-Harb et al. (1995); (15) Caraveo et al. (2003); (16) van der Swaluw et al. (2004); (17) Pivovaroff (2003); (18) Giacani et al. (2001); (19) Pellizzoni et al. (2002); (20) Camilo et al. (2001); (21) Braje et al. (2002); (22) Gaensler et al. (2003a); (23) Wang et al. (2002).

bow-shocks is of paramount importance to obtain information on the structure of the external regions of the pulsar magnetosphere (geometry and particle energies) and properties of the interstellar medium (density, ionisation).

2. Classification of Pulsar Bow-shocks

A clear classification of pulsar bow-shocks is still not well defined owing to the poor sample of available objects, their weakness and the difficulty to distinguish them from other kinds of PWNe (not all bow-shaped PWNe are bow-shocks). As a first step in order to better assess their properties as a population we have built a catalogue (Table 1) based on the identification criteria described in the previous chapter. Only 10 bow-shocks are firmly detected in $H\alpha$ and/or in radio and X–rays. Another set of 10 candidates needs confirmation. Known bow-shocks are tipically associated to energetic and nearby pulsars (including few millisecond pulsars) with “normal” characteristics apart from their high $\dot{E}_{rot} \times V^2/d^2$ values. About 50% of the sources are observed in the X–ray and radio bands and another ∼50% is visibile only in Hα. Only one case (“The Black Widow”) is firmly detected in both energy bands. According to their morphologies, two general classes of bow-shocks can be identified; (1) “comet shaped” bow-shocks, as the Guitar nebula (Figure 1), characterized by high speed (>1000 km/s) and proper motion in the plane of the sky; (2) "bullet" bow-shocks (Figure 2) characterized by low pulsar velocity and/or motion along the line of sight. The first class allows to study wind asymmetries and gradient density in the ISM. The latter class includes objects more difficult to identify due to the absence of peculiar geometrical strucures, but it includes a potentially wider sample of bow-shocks useful for population studies.

The search for new pulsar bow-shocks could improve luminosity models poorly constrained by the existing observations. The expected Hα luminosity (see e.g. Pellizzoni et al. (2002), and references therein) is roughly proportional to the neutron star velocity V, its rotational energy loss $\dot{E}_{\rm rot}$, and the fraction X of neutral hydrogen in the interstellar medium: $L_{\rm H\alpha} \propto V\dot{E}_{\rm rot}X$. This relation fits known sources quite well, but its dependence on the neutral hydrogen fraction, a very uncertain parameter, implies rather uncertain Hα flux predictions even in case of nearby pulsars clearly showing bow-shocks at other wavelengths. For example, Geminga shows a striking bow-shock in X–rays but it is undetected in Hα (Caraveo et al. 2003) implying a remarkably low neutral hydrogen fraction <0.01. A possible explanation of this could be that the synchrotron emission from the shock or from the neutron star could pre-ionize the ISM inhibiting Hα emission. Exahustive broad-band emission models for pulsar bow-shocks should then properly account for synchrotron losses and adiabatic expansion of the PWN which depend on many input parameters reflecting the evoulutionary state of the system and the ambient conditions. Thus, such models are clearly speculative without new valuable multiwalength observations and an in-depth analysis of existing X–rays and Hα surveys improving the current sample of pulsar bow-shocks.

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