

A Key to Pulsar Wind Bubble Morphologies: Hydrodynamical Simulations

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Abstract. We present a model of a pulsar-driven supernova remnant, by using a hydrodynamics code, which simulates the evolution of a pulsar wind nebula when the pulsar is moving at a high velocity through its expanding supernova remnant. The simulation shows four different stages of the pulsar wind nebula: the supersonic expansion stage, the reverse shock interaction stage, the subsonic expansion stage and ultimately the bow shock stage. Due to the high velocity of the pulsar, the position of the pulsar is located at the head of the pulsar wind bubble, after the passage of the reverse shock. The resulting morphology of the pulsar wind bubble is therefore similar to the morphology of a bow shock pulsar wind nebula. We show how to distinguish these two different stages, and apply this method to the SNR G327.1–1.1, for which we argue that there is *no* bow shock around its pulsar wind nebula.

1. Introduction

The dynamics of the interior of a young pulsar-driven supernova remnant (SNR) is dominated by the continuous injection of energetic particles by a relativistic pulsar wind. This pulsar wind is driven by the spin-down energy of the pulsar, and is terminated by a strong MHD shock (Rees & Gunn 1974). The pulsar wind blows a pulsar wind nebula (PWN), which is bounded by a strong PWN shock, into the freely expanding ejecta of its surrounding young SNR. A young SNR is characterized by a blast wave propagating into the interstellar medium (ISM) and a reverse shock, which propagates back into the SNR interior once the SNR blast wave has swept up a few times the ejecta mass (McKee & Truelove 1995). When the reverse shock collides with the PWN shock, the supersonic expansion stage of the PWN is terminated: the PWN shock bounding the hot pulsar wind bubble disappears.

Hydrodynamical simulations of the above process have been performed by several authors (van der Swaluw et al. 2001; Blondin et al. 2001) for a centered pulsar. These simulations bear out that the timescale for the reverse shock interaction stage is comparable with the lifetime of the supersonic expansion

stage. Ultimately the expansion of the PWN proceeds subsonically inside the relaxed Sedov-Taylor SNR, when the reverberations of the reverse shock have vanished.

In this paper we present a hydrodynamical simulation of a PWN when the pulsar is *moving* at a high velocity through the expanding SNR. The simulation shows that due to the high velocity of the pulsar, the position of the pulsar is off-centered with respect to its PWN, after the passage of the reverse shock. Furthermore, the simulation shows a deformation of the PWN into a bow shock when the motion of the pulsar becomes supersonic. This occurs at half the crossing time, or equivalently when $R_{\text{psr}}/R_{\text{snr}} \approx 0.677$, where R_{psr} is the distance of the pulsar from the center of the SNR, and R_{snr} is the radius of the blast wave. The crossing time indicates the age of the SNR when the pulsar overtakes the shell of its remnant, while the latter is in the Sedov-Taylor stage. Both values are in complete agreement with analytical work performed by van der Swaluw et al. (1998).

2. The Evolution of a PWN Inside a SNR

2.1. The Hydrodynamical Simulation

We use a second order, properly upwinded hydrodynamics code (described in Downes & Ray 1999) to simulate the dynamics of the interaction between a pulsar wind and a supernova remnant. The hydrodynamics equations are integrated in cylindrical symmetry, and the boundary conditions are taken as gradient zero everywhere except on the $r = 0$ boundary, where they are set to reflecting. The simulation is performed in the rest frame of the pulsar, which is moving at a velocity of $V_{\text{psr}} = 1000 \text{ km s}^{-1}$. Thermal energy is deposited at a constant rate in a small sphere centered around the pulsar, such that the pulsar wind luminosity equals $L_{\text{pw}} = 10^{38} \text{ ergs s}^{-1}$. Mass is also deposited into this region at a rate chosen such that the pulsar wind terminal velocity equals $v_{\infty} = 30000 \text{ km s}^{-1}$. The supernova itself is modeled by initializing a sphere of radius 0.25 pc, or 21 grid cells, with a high thermal energy and density such that the total energy contained in the sphere is $E_0 = 10^{51} \text{ ergs}$, while the mass is $M_{\text{ej}} = 3 M_{\odot}$. This means that the total injected energy by the pulsar wind during its stay in the SNR interior equals $E_{\text{pw}} = L_{\text{pw}} t_{\text{cr}} \ll E_0$, where t_{cr} is the crossing time. The surrounding medium has a density of $\rho_0 = 10^{-24} \text{ g cm}^{-3}$. The total grid size equals 7 by 14 parsec with an associated 600 by 1200 grid cells.

2.2. An Off-Centered Pulsar Inside Its PWN

Figure 1 shows a logarithmic gray-scale representation of the density distribution of the PWN/SNR system at two different stages. The upper profile shows the system shortly after the passage of the reverse shock. The simulation bears out that due to the high velocity of the pulsar, the position of the pulsar is off-center with respect to its surrounding PWN, after the passage of the reverse shock. A typical timescale for the age of such a system was given by van der Swaluw (2004):

$$t_{\text{rev}} = 1,045 E_{51}^{-1/2} \left(\frac{M_{\text{ej}}}{M_{\odot}} \right)^{5/6} n_0^{-1/3} \text{ years}; \quad (1)$$

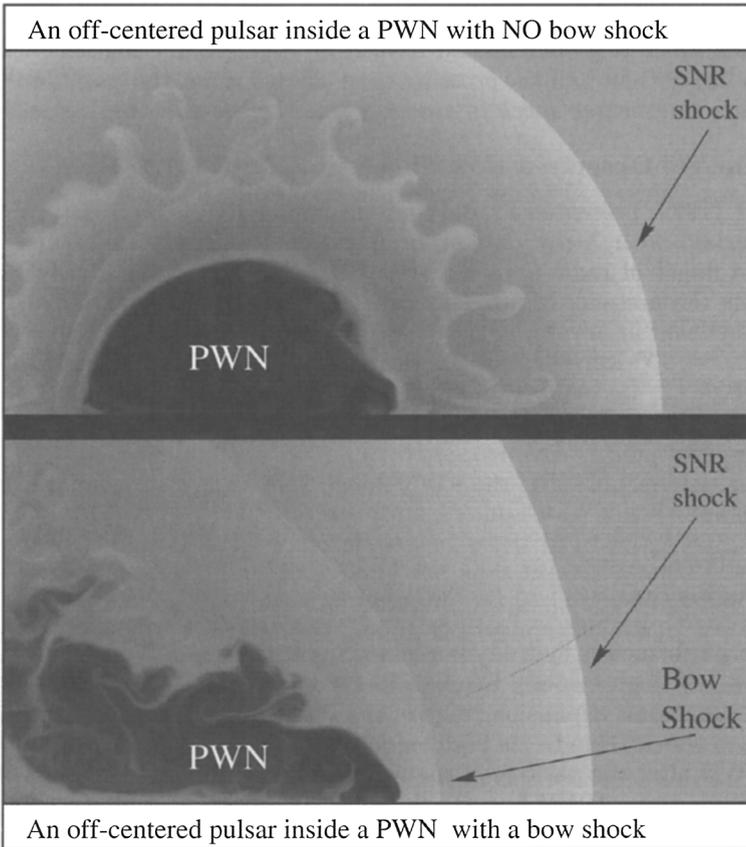


Figure 1. The PWN/SNR system at an age of $t = 2600$ yrs (upper panel) and $t = 10200$ yr (bottom panel).

here E_{51} is the total mechanical energy of the SNR in units of 10^{51} ergs, M_{ej} is the ejecta mass and $n_0 = \rho_0/2.34 \times 10^{-24}$ g cm $^{-3}$ is the ambient hydrogen number density.

The lower profile shows the PWN/SNR system after the formation of the bow shock. In this case the position of the pulsar is again located at the head of the PWN, but the conditions $R_{psr}/R_{snr} \geq 0.677$ and the age $t \geq 0.5t_{cr}$ are satisfied, where t_{cr} equals the crossing time of the pulsar (van der Swaluw 2004):

$$t_{cr} \simeq 1.4 \times 10^4 E_{51}^{1/3} V_{1000}^{-5/3} n_0^{-1/3} \text{ years}; \quad (2)$$

here V_{1000} is the velocity of the pulsar in units of 1000 km s $^{-1}$.

The most important issue of the present simulation for interpreting the evolutionary stage of plerionic components (i.e., the observational counterpart of

a PWN) inside composite remnants is the off-center position of the pulsar inside its PWN. In order to determine whether a PWN inside a composite remnant is in the *bow shock stage* one should have $R_{\text{psr}}/R_{\text{snr}} \geq 0.677$ together with an age which is larger than half the crossing time. If this is not the case then the PWN is in either the *reverse shock interaction stage* or the *subsonic expansion stage*.

2.3. Do We Observe a Bow Shock in SNR G327.1–1.1?

Sun et al. (1999) presented a radio contour map of SNR G327.1–1.1, using MOST data overlaid with X-ray data from *ROSAT*. The X-ray emission is centered around a finger of radio emission sticking out of a central radio bright region, indicating the presence of a pulsar wind. Following Sun et al. (1999), the SNR can be modeled in X-rays by the following set of parameters: $E_{51} = 0.23$, $n_0 = 0.10$, $V_{\text{psr}} = 600 \text{ km s}^{-1}$ and an age of $t = 1.1 \times 10^4$. Using Equation (2) to calculate t_{cr} , we get a value of 4.3×10^4 years: the age of the remnant is lower than half the crossing time. Furthermore the position of the PWN tail containing the pulsar, with respect to the SNR shell, yields $R_{\text{psr}}/R_{\text{snr}} < 0.677$. Therefore we conclude that the PWN inside SNR G327.1–1.1 is not bounded by a bow shock.

3. Conclusion

We have performed a hydrodynamical simulation of a PWN, when the pulsar is moving at a high velocity through its associated SNR. The simulation shows that the supersonic expansion stage of the PWN is terminated by the passage of the reverse shock. Due to its high velocity, the pulsar is positioned at the head of the PWN after the passage of the reverse shock. The resulting morphology is similar to that of a PWN bow shock, which is formed at half the crossing time when the pulsar is located at a radius $R_{\text{psr}} \simeq 0.677R_{\text{snr}}$. We have applied these criteria to the SNR G327.1–1.1 and concluded that the PWN inside this system has not been deformed into a bow shock.

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