DO WE REALLY OBSERVE A BOW SHOCK IN N157B...?

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ABSTRACT

I present a model of a pulsar wind interacting with its associated supernova remnant. I will use the model to argue that one can explain the morphology of the pulsar wind nebula inside N157B, a supernova remnant in the Large Magellanic Cloud, without the need for a bow shock interpretation. The model uses a hydrodynamics code which simulates the evolution of a pulsar wind nebula, when the pulsar is moving at a high velocity (1 000 km/sec) through the expanding supernova remnant. The evolution of the pulsar wind nebula can roughly be divided into three stages. In the first stage the pulsar wind nebula is expanding supersonically through the freely expanding ejecta of the progenitor star (\(\sim 1 \text{ 000 years}\)). In the next stage the expansion of the pulsar wind nebula is not steady, due to the interaction with the reverse shock of the supernova remnant; the pulsar wind nebula oscillates violently between contraction and expansion, but will ultimately relax towards a steady subsonic expansion (\(\sim 1 \text{ 000} - 10 \text{ 000 years}\)). The last stage occurs when the head of the pulsar wind nebula, containing the active pulsar, deforms into a bow shock (\(> 10 \text{ 000 years}\)), due to the motion of the pulsar becoming supersonic. Ultimately it is this bow shock structure bounding the pulsar, which directly interacts with the shell structure of the supernova remnant, just before the pulsar breaks out of the supernova remnant. I will argue that the pulsar wind nebula inside N157B is currently in the second stage of its evolution, i.e. the expansion of the pulsar wind nebula is subsonic and there is no bow shock around the pulsar wind bubble. The strongly off-centered position of the pulsar with respect to its pulsar wind nebula is naturally explained by the result of the interaction of the reverse shock with the pulsar wind nebula, as the simulation bears out.

A PULSAR WIND INSIDE A SUPERNOVA REMNANT

A supernova explosion marks the end of the evolutionary track of a massive star, but launches the beginning of the evolution of a supernova remnant (SNR). If the fossil of the progenitor star is an active pulsar, the associated pulsar wind drives a pulsar wind nebula (PWN) into the surrounding medium (Rees and Gunn 1974). The evolution of the PWN is coupled and determined by the evolution of the SNR, because the total energy release of the relativistic pulsar wind over the pulsar’s lifetime is small (\(10^{49} - 10^{50} \text{ erg}\)) compared with the total mechanical energy of the SNR (\(10^{51} \text{ erg}\)).

A young SNR (\(\sim 100 - 1 \text{ 000 years}\)) consists of a twofold shock structure, i.e. a forward shock which propagates into the interstellar medium (ISM) and a reverse shock which forms due to the deceleration of the forward shock by the surrounding ISM (McKee 1974). When the forward shock has swept up a comparable amount of mass as was ejected in the explosion event, the reverse shock propagates back into the interior of the SNR, where the PWN is expanding through the freely expanding ejecta of the progenitor star. As the reverse shock encounters the PWN, the latter is crushed, due to the huge pressure downstream of the reverse shock relative to the pressure inside the PWN (van der Swaluw et al. (2001); Blondin et al. (2001)).

Van der Swaluw et al. (2001) have shown that in the case of a centered pulsar, the interaction between the reverse shock and the centrally powered PWN results in an unsteady expansion stage, during which the interior of the pulsar wind bubble adjusts itself to the pressure of the surrounding SNR. Ultimately the expansion of the PWN becomes subsonic. However, when the pulsar is born with a kick velocity, the position of the active pulsar has become off-center with respect to the SNR at this stage, and will ultimately overtake and break through the shell of the decelerating...
SNR. Before this break-through event the motion of the pulsar becomes supersonic which deforms the head of the PWN, containing the active pulsar, into a bow shock (van der Swaluw et al. 1998).

In this paper I present results from a hydrodynamical simulation, carried out with the Versatile Advection Code (VAC)\(^1\). The simulation describes the evolution of a pulsar wind nebula when the pulsar is moving at a high velocity (1000 km/sec) through its associated supernova remnant. The simulation shows that the position of the pulsar is strongly off-centered with respect to its pulsar wind bubble, after the interaction between the reverse shock and the PWN. Furthermore the simulation confirms the formation of a bow shock at a later stage of the PWN, as the motion of the pulsar becomes supersonic. The pulsar inside the SNR N157B is strongly off-centered with respect to its PWN. However the age of the remnant is rather young to explain the PWN morphology as a bow shock. Therefore I propose a scenario for which the pulsar wind nebula inside N157B has been recently crushed by the reverse shock. The simulation shows that this explains the off-centered position of the pulsar with respect to its PWN, the age of the remnant and the overall morphology of the PWN in a natural way.

**IMPORTANT TIMESCALES FOR PWN EVOLUTION**

Initially the PWN is bounded by a strong shock propagating into the freely expanding ejecta of the progenitor star. As the forward shock of the SNR is expanding into the ISM, it starts to decelerate. McKee and Truelove (1995) define a timescale \(t_{\text{ST}}\), which marks the age of the remnant when it has swept up roughly 1.61 times the ejected mass \(M_{\text{ej}}\). They show that when the age of the remnant \(t_{\text{snr}}\), approximately equals \(t_{\text{snr}} \approx 5 \ t_{\text{ST}}\), the reverse shock hits the center of the SNR. Therefore one can roughly equal this timescale with the age at which the PWN interacts with the reverse shock:

\[
t_{\text{rev}} \approx 5t_{\text{ST}} = 1.045E_{51}^{-1/2} \left( \frac{M_{\text{ej}}}{M_\odot} \right)^{5/6} n_0^{-1/3} \text{ years ,}
\]

here \(E_{51}\) is the total mechanical energy of the SNR in units of \(10^{51}\) erg and \(n_0\) is the ambient hydrogen number density assuming an interstellar composition of 10 H : 1 He. The above timescale is very close to the one given by Reynolds and Chevalier (1984) and marks the end of the stage of the PWN during which it is expanding supersonically.

After the interaction of the PWN with the reverse shock, the pulsar is propagating through a medium which has been reheated due to the passage of the reverse shock. Therefore the motion of the pulsar and the expansion of the PWN are both subsonic. Van der Swaluw et al. (1998) have shown that the motion of the pulsar becomes supersonic and deforms the pulsar wind bubble into a bow shock, when the position of the pulsar \(R_{\text{psr}}\), with respect to the radius of the SNR shock \(R_{\text{snr}}\), equals:

\[
R_{\text{psr}} = 0.677R_{\text{snr}},
\]

assuming a Sedov-Taylor expansion rate for the SNR. This occurs at roughly half the crossing time, i.e. the age of the SNR when the pulsar overtakes the shell of the remnant:

\[
t_{\text{cr}} \approx 1.4 \times 10^4 E_{51}^{1/3} V_{1000}^{-5/3} n_0^{-1/3} \text{ years ,}
\]

here \(V_{1000}\) is the velocity of the pulsar in units of 1000 km/sec. Using the above timescales, one can roughly summarise the PWN evolution inside a Sedov-Taylor SNR as:

- a supersonically expansion stage \((t_{\text{snr}} < t_{\text{rev}})\)
- a subsonically expansion stage \((t_{\text{rev}} < t_{\text{snr}} < 0.5t_{\text{cr}})\)
- a bow shock stage \((0.5t_{\text{cr}} < t_{\text{snr}} < t_{\text{cr}})\)

**HYDRODYNAMICAL SIMULATIONS**

**Simulation Method**

I performed a hydrodynamical simulation of a SNR with a mechanical energy of \(E_0 = 10^{51}\) erg and a total ejecta mass of \(M_{\text{ej}} = 3M_\odot\) expanding into a uniform ISM with a hydrogen number density of \(n_0 = 0.43\). The simulation is performed in the restframe of the pulsar wind, placed at the (explosion) center of the remnant with a constant luminosity \(L_{\text{pw}} = 10^{38}\) ergs/sec and a pulsar velocity \(V_{\text{psr}} = 1000\) km/sec. The pulsar wind luminosity is taken to be constant throughout the simulation. This is required in order to resolve the pulsar wind termination shock. The results are certainly not changed qualitatively, because the total integrated energy input by the pulsar wind is only a \(\sim 5\%\) of

\[^1\text{See} \text{http://www.phys.uu.nl/~toth/}\]
the total mechanical energy of the SNR at the end of the simulation. This insures that the evolution of the pulsar wind bubble is completely determined by its surrounding evolving SNR. I used the Versatile Advection Code (Tóth 1996) to solve the equations of gas dynamics on a uniform grid with axial symmetry, using a cylindrical coordinate system $(R, z)$ in the restframe of the pulsar. I simulate the pulsar wind by depositing mass $M$ and energy $L_{pw}$ continuously in a few grid cells concentrated around the position of the pulsar. The terminal velocity of the pulsar wind is determined from these two parameters, i.e. $v_\infty = \sqrt{2L_{pw}/M}$, and has a value much larger than all the other velocities of interest in the simulation. The current version of the VAC code does not include relativistic hydrodynamics, therefore the best approach available is to take an adiabatic index of the relativistic fluid $\gamma_{pwn} = 5/3$.

**Fig. 1.** Logarithmic gray-scale representation of the density distribution at an age $t_{snr} = 2250$ years.

**The Supersonically Expansion Stage (Figure 1)**

Figure 1 shows the density profile of the PWN/SNR system at an age of $t_{snr} = 2250$ years. The PWN has been dragged towards the reverse shock by the motion of the pulsar. The front part of the PWN has already been crushed by the reverse shock (the part indicated in the figure by interaction regime), it will take another $\sim 500$ years before the whole PWN will be completely crushed by the reverse shock. One can clearly distinguish the forward shock, contact discontinuity, PWN shock and the pulsar wind (termination) shock. In the figure the cross corresponds with the pulsar position.
The subsonically Expansion Stage (Figure 2)

Figure 2 shows the density profile of the PWN/SNR system at an age of $t_{\text{snr}} = 3000$ years, at which time the whole PWN has been crushed by the reverse shock. One can clearly distinguish the crushed relic part of the bubble blown in the initial stage of the PWN, when it was bounded by a strong shock. The pulsar is positioned at the head of the PWN (indicated by a cross again), but the feature ahead of the pulsar is not a bow shock but is the reflected reverse shock. Notice that although there is no bow shock around the PWN, the pulsar is strongly off-centered with respect to the PWN, after its interaction with the reverse shock.

The bow shock stage (Figure 3)

Figure 3 shows the density profile of the PWN/SNR system at an age of $t_{\text{snr}} = 15750$ years, at the end of the simulation. The pulsar is approaching the shell of the SNR and the head of the pulsar wind bubble, containing the active pulsar, has been deformed into a bow shock. The simulation confirms the formation of a bow shock at the head of the PWN, at half the crossing time $t_{\text{cr}}$, when the position of the pulsar $R_{\text{psr}}$ with respect to the shell of the SNR $R_{\text{snr}}$ equals $R_{\text{psr}} \approx 0.677R_{\text{snr}}$, as predicted by van der Swaluw et al. (1998). Notice that the lengthscale of the PWN is small compared with the SNR shock structure. This confirms the approximation made by van der Swaluw et al. (2003) to model the break-through event of a pulsar wind through the shell of its SNR, by neglecting the curvature of the SNR blast wave.
Summary
The results of the simulation performed in this paper clearly show the three stages of an evolving PWN in an expanding SNR; a supersonically expansion stage, a subsonically expansion stage and a bow shock stage. The simulation bears out that after the interaction between the reverse shock and the PWN, the pulsar is strongly off-centered with respect to its PWN, while the motion of the pulsar is still subsonic. Furthermore the simulation shows the formation of a bow shock at the head of the PWN, containing the active pulsar, at a later stage, when the motion of the pulsar becomes supersonic. However, the expansion of the relic part of the PWN, blown in the supersonically expansion stage, remains subsonic.

THE PULSAR WIND NEBULA INSIDE SNR N157B

The bright X-ray object N157B is a young SNR dominated by plerionic emission originating from the PWN inside this object (Dickel and Wang 2003). The age of the remnant is approximately 5 000 years old (Wang and Gotthelf 1998) and contains a 16 ms pulsar (Marshall et al. 1998). The velocity of this pulsar is high ($V_{\text{psr}} \approx 1 000$ km/sec), if one assumes that the pulsar was born in the central region of the bright radio emission (Lazendic et al. 2000). Wang and Gotthelf (1998) argue for a bow shock interpretation of the PWN in N157B. A classical example of a pulsar wind bow shock inside its associated SNR is the remnant CTB80, with an estimated age of $t_{\text{snr}} \approx 100 000$ years and an associated pulsar with a spindown luminosity of $L_{\text{pw}} \approx 4.0 \times 10^{36}$ erg/sec. These values show a remarkable contrast with the parameters of the SNR N157B ($t_{\text{snr}} \approx 5 000$ years and $L_{\text{pw}} \approx 4.8 \times 10^{38}$ erg/sec). Furthermore from
Figure 2 of Wang et al. (2001) it seems like the position of the pulsar is more or less centered in the SNR. This is in contrast with the analysis performed by van der Swaluw et al. (1998), which predicts $R_{\text{psr}}/R_{\text{snr}} \geq 0.677$ for a bow shock PWN, a result confirmed by the simulation in this paper.

In order to solve the issues mentioned above, I propose the following evolutionary stage for the PWN inside SNR N157B: the PWN has recently been crushed by the reverse shock of its associated SNR. Due to the combination of the reverse shock interaction and the high velocity of the pulsar, the position of the pulsar is strongly off-centered with respect to its PWN, as shown by the results of the simulations performed in this paper. Figure 2 represents the current morphology of N157B, where the relic PWN represents the central bright parts of the radio and X-ray emission in N157B. This scenario automatically implies the absence of a bow shock in N157B. Furthermore the age of N157B is in rough agreement with this scenario ($t_{\text{rev}} < t_{N157B} < 0.5t_{\text{cr}}$).

**CONCLUSION**

I 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 one can roughly distinguish between a supersonically expanding PWN, a subsonically expanding PWN and a stage during which part of the PWN is bounded by a bow shock, due to the supersonic motion of the pulsar. After the interaction between the PWN and the reverse shock the position of the pulsar has become off-centered with respect to its PWN. Therefore one should be careful in distinguishing a young subsonically expanding PWN ($t_{\text{rev}} < t_{\text{pwn}} < 0.5t_{\text{cr}}$) and an older PWN with a bow shock around its pulsar ($0.5t_{\text{cr}} < t_{\text{pwn}} < t_{\text{cr}}$). In the case of N157B, I have argued for a no as an answer to the title of this paper.

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