MHD Interaction of Pulsar Wind Nebulae with SNRs and with the ISM

E. van der Swaluw

FOM-Institute for Plasma Physics Rijnhuizen, P.O. Box 1207, 3430 BE
Nieuwegein, The Netherlands

Abstract

In the late 1960s the discovery of the Crab pulsar in its associated supernova remnant, launched a new field in supernova remnant research: the study of pulsar-driven or plerionic supernova remnants. In these type of remnants, the relativistic wind emitted by the pulsar, blows a pulsar wind nebula into the interior of its supernova remnant. Now, more then forty years after the discovery of the Crab pulsar, there are more then fifty plerionic supernova remnants known, due to the ever-increasing capacity of observational facilities. These observational studies reveal a Zoo of complex morphologies over a wide range of frequencies, indicating the significance of the interaction between a pulsar wind nebula with its surrounding supernova remnant. A pulsar which gained a kick velocity at birth, will ultimately break outside of its remnant, after which the pulsar wind nebula interacts directly with the interstellar medium. In general these pulsar wind nebulae are bounded by a bow shock, due to the supersonic motion of the pulsar. There are a few examples known of these pulsar-powered bow shocks, a number which is slowly increasing.

I will review our current understanding of the different evolutionary stages of a pulsar wind nebula as it is interacting with its associated supernova remnant. Therefore I will discuss both analytical and more recent numerical (M)HD models. The four main stages of a pulsar wind nebula are: the supersonic expansion stage, the reverse shock interaction stage, the subsonic expansion stage and ultimately the stage when the head of the bubble is bounded by a bow shock, due to the supersonic motion of the pulsar. Ultimately this pulsar wind nebula bow shock will break through its associated remnant, after which the pulsar-powered bow shock will interact directly with the interstellar medium. I will discuss recent numerical models from these type of pulsar wind nebulae and their morphology.

Key words:
1 Introduction

After the explosion of a massive star, the outer layers of the star are ejected into the circumstellar or interstellar medium (ISM). This event gives birth to a supernova remnant (SNR): an expanding bubble of million-degree gas. A plerionic supernova remnant results from those explosion which also yield a fast rotating neutron star, which blows a pulsar wind nebula (PWN) into the interior of its remnant. Recent models by Heger et al. (2003) indicate a mass range of the progenitor star between 10 to 25 solar masses, in order to obtain both a supernova explosion and a neutron star. The ejecta from the progenitor star are driven into the surrounding medium, which at early stages yields a double-shock structure (McKee 1974; McKee and Truelove, 1995): a forward shock propagating into the surrounding medium, and a reverse shock which forms almost immediately, shock-heating the freely expanding ejecta to X-ray emitting temperatures. Ultimately, as the forward shock has swept up a few times the ejecta mass, the reverse shock propagates towards the center of the remnant, where its energy is dissipated into weak shock waves and sound waves (Cioffi et al. 1998). In recent years the number of plerionic remnants has slowly been increasing (see Kaspi et al. (2004) for a recent overview), making this type of remnant a rather common type of SNR. The presence of a PWN in the interior of a remnant obviously increases the complexity of the internal dynamics of the remnant, although the energy input from a pulsar wind over its lifetime is small, therefore its evolution couples to the remnant’s evolution. The PWN itself is driven by a pulsar wind (Pacini and Salvati, 1973; Rees and Gunn, 1974), which is believed to be highly relativistic and magnetized (see e.g. Kennel and Coroniti, 1984; Gallant et al., 2002). The wind itself consists of an electron-positron plasma, possibly together with an ion ingredient (Hoshino et al., 1992), and is ultimately terminated by a strong MHD shock. At the site of the wind termination shock, particles are being accelerated. These accelerated particles radiate part of their energy away as synchrotron radiation, while being advected away from the wind termination shock. These regions of the PWN are observed over a wide range of frequencies as the actual plerion.

2 Plerionic supernova remnants with a centered pulsar

2.1 Analytical models: supersonic and subsonic expansion

The morphology of a PWN, as it is still interacting with the freely expanding ejecta of its associated remnant, can be divided into three regions separated by three interfaces (see left panel Figure 1): A/ the pulsar wind cavity, B/
the pulsar wind (synchrotron) bubble, and C/ the shell of swept-up ejecta material. Whereas the three interfaces are I/ the pulsar wind termination shock, II/ the contact discontinuity and III/ the PWN shock. The PWN shock is propagating through the freely expanding ejecta (see right panel Figure 1) and is being accelerated \( R_{\text{pwn}} \propto t^{6/5} \) for a uniform density of the ejecta) as long as the pulsar wind luminosity is constant (Reynolds & Chevalier 1984, Chevalier & Fransson 1992, van der Swaluw et al. 2001). This stage of the PWN evolution has been called the supersonic expansion stage in literature and its timescale is determined by when the reverse shock of the SNR collides with the PWN shock. After the passage of the reverse shock, the expansion of the PWN will be subsonic (Reynolds & Chevalier 1984).

McKee and Truelove (1995) give analytical approximations for the trajectories of the forward shock and the reverse shock for the case in which both the ambient medium and the ejecta have a uniform density. The reverse shock reaches the center of the remnant at a timescale of

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

here \( E_{51} \) is the total mechanical energy of the SNR in units of \( 10^{51} \) erg, \( n_0 \) is the ambient hydrogen number density assuming an interstellar composition of 10 H : 1 He, and \( M_{\text{ej}} \) is the ejecta mass. The above equation yields an upper limit for the timescale of the supersonic expansion stage of the PWN. The associated maximum radius of the PWN can be calculated using equation 12 from van der Swaluw et al. (2001), which yields:

\[
R_{\text{col}} \simeq 3.69 L_{38}^{1/5} M_{\text{ej}}^{1/2} n_0^{-2/5} \text{ parsec},
\]

here \( L_{38} \) is the luminosity of the (constant) pulsar wind in units of \( 10^{38} \) ergs/sec.

The above approximations yield rough estimates for the timescale and the maximum size of the PWN in the supersonic expansion stage, when both the ejecta and the ambient medium have a uniform density. A more sophisticated analysis would have to include 1/ a non-uniform density of the ejecta (Truelove and McKee, 1999) 2/ a non-uniform ambient medium which has been adapted by the activity of the wind from the progenitor star (see e.g. Garcia-Segura et al., 1996) and 3/ the decay of the pulsar wind luminosity (see e.g. Bucciantini et al. 2004). Chevalier (2004) has recently used these three aspects into a model to deduce the supernova type of several observed SNRs.
Fig. 1. The left panel shows a schematic representation of a PWN expanding in the freely expanding ejecta. There are three interfaces: I the pulsar wind termination shock; II the contact discontinuity dividing shocked pulsar wind material from shocked ejecta; III the PWN shock. Region A is the pulsar wind cavity, region B is the pulsar wind bubble and region C is the shell containing the swept-up ejecta. The right panel shows a logarithmic gray-scaling of the density distribution of a plerionic SNR from a hydrodynamical simulation (van der Swaluw et al. 2004). Apart from all the interfaces and regions from the left panel one can distinguish IV the reverse shock and V the forward shock. Region D consists of freely expanding ejecta, whereas region E denotes the interstellar medium.

2.2 Hydrodynamical simulations: the reverse shock interaction

In recent years numerical simulations have yielded a more sophisticated model for plerionic supernova remnants with a centered pulsar ($V_{\text{psr}} = 0$) and the associated reverse shock interaction. These simulations (e.g. van der Swaluw et al. 1998, 2001; Blondin et al. 2001; Bucciantini et al. 2003) confirm the division into an initial supersonic expansion stage and a subsequent subsonic expansion stage. However these simulations all very clearly show that the transition between these two stages is not direct, but via a non-steady expansion stage of the PWN: the PWN is crushed, shortly after the passage of the reverse shock, in order to gain pressure balance with the surrounding SNR interior. The timescale of this crushing event seems to be comparable to the lifetime of the supersonic expansion stage (see Figure 2), which implies that a significant amount of observed PWNe should be in this intermediate stage of their evolution. The characteristics of these type of crushed PWNe would be 1/ small size of the PWN with respect to the SNR radius (see Figure 2), 2/ very bright emission due to the increase of the magnetic field strengths
Fig. 2. The upper panel shows the radius of the PWN as a function of time. The lower panel shows the ratio of the PWN radius over the blastwave radius from the SNR as a function of time. For both panels the solid line corresponds with the supersonic expansion stage, the dashed line corresponds with the crushing stage and the dotted line marks the stages in which the PWN relaxes towards the subsonic expansion stage. The simulation results are adapted from van der Swaluw et al. (2001).

(caused by the decrease of the bubble’s size), and 3/ a synchrotron cooling break at relative low frequency due to the increasing magnetic field strength (Gallant et al., 2002). After the PWN has been crushed, the bubble oscillates between expansion and contraction, due to the reverberations of the reverse shock interaction, after which the PWN relaxes towards a steady subsonic expansion.
2.3 Magneto-hydrodynamical simulations: elongated PWNe

The first images of the Crab Nebula already revealed the elongation of the pulsar wind bubble. It is very clear now that the Crab Nebula is not unique but that this is a rather common aspect of supersonically expanding PWNe. Begelman and Li (1998) developed a semi-analytical model to explain the elongation of the Crab Nebula as a result of the toroidal magnetic fields inside the PWN. The toroidal magnetic fields introduce a pressure gradient along the minor axis of the bubble, which yields a high pressure (fast expansion) at the major axis and a low pressure (slow expansion) at the minor axis. Magneto-hydrodynamical simulations (van der Swaluw, 2003; Komissarov and Lyubarsky, 2004; Del Zanna et al., 2004) have confirmed these results. Some of these simulations (Komissarov and Lyubarsky, 2004; Del Zanna et al., 2004) have been performed such that the condition of spherical symmetry is no longer enforced, instead an anisotropic pulsar wind, which is more consistent with pulsar wind theory, has been used. These simulations yield a more complex termination shock structure and post-shock flow. The X-ray synchrotron map calculated from these simulations by Komissarov and Lyubarsky (2004) yields a similar jet-torus pattern as is observed in the X-ray Chandra map of the Crab Nebula.

3 Moving pulsars

It is believed that pulsars can obtain a velocity at birth, due to for example asymmetric supernova explosions. Recent studies (Arzoumanian et al. 2002) show strong evidence for a two-component velocity distribution of 90 and 500 km s\(^{-1}\) for isolated radio pulsars. The velocity of a pulsar will obviously influence the evolution of the PWN, as will be discussed below.

In the supersonic expansion stage, the expansion velocity of the PWN shock is high, i.e. typically 1,000-5,000 km/sec. These values are much higher then typical values of pulsar velocities as mentioned above. Therefore before the passage of the reverse shock, the evolution of the PWN will not be influenced by the motion of the pulsar.

The time for the reverse shock to collide with the complete PWN shock surface scales roughly linear with the velocity of the pulsar, as was shown by van der Swaluw et al. (2004). For large velocities, this collision process can be a significant fraction of the total lifetime of the remnant. The model from van der Swaluw et al. (2004) assume a constant uniform density of the ISM. In contrast, Blondin et al. (2001) performed simulations for which the pulsar is steady (\(V_{psr} = 0\)), whereas the ISM is non-uniform. They show that for
such a configuration the collision of the reverse shock with the whole of the PWN shock surface is also not instantaneous. It should be stressed that the exact collision process and its associated timescale for a PWN, will in general depend on a combination of the motion of the pulsar and the structure of the surrounding medium in which the SNR forward shock propagates. Both the simulations from Blondin et al. (2001) and van der Swaluw et al. (2004) show that after the crushing event of the PWN, there is a clear two-component PWN structure: the relic PWN, which contains a large fraction of the injected electrons during the pulsar wind’s lifetime, and the head of the PWN, which is supplied by freshly injected electrons by the pulsar wind. The relic PWN would therefore radiate brightly at radio frequencies (also due to the increased magnetic field strength). The PWN head would be a weaker radio source but be bright at X-ray frequencies, which is lacking in the relic PWN, due to the short synchrotron lifetime of X-ray electrons. N157B and G327.1-1.1 are two examples which clearly show such a morphology, indicating that these two SNRs are examples of PWNe for which the supersonic expansion stage has been terminated by the passage of the reverse shock.

The simulation from van der Swaluw et al. (2004) shows that after the passage of the reverse shock, the head of the PWN, containing the young pulsar will ultimately deform into a bow shock. This transition occurs once the pulsar motion becomes larger compared with the sound speed of the surrounding SNR material. Exact numbers for this transition can be given when the pulsar propagates through a Sedov-Taylor remnant (van der Swaluw et al. 1998), i.e. the transition occurs when the position of the pulsar equals \( \approx 0.667 \times \) the blastwave radius of the SNR at roughly half the crossing time. However, most pulsars are expected to take over their remnant’s shell when the SNR has already made its transition to the pressure-driven snowplow stage, of which PSR1951+32 in the SNR CTB80 is an excellent example.

After the break-through event of a PWN bow shock through its associated SNR, the PWN is interacting directly with the ISM material. Currently there are only a few PWNe bow shocks known of which the Mouse (Gaensler et al. 2004) is the brightest one in both radio and X-rays. However, up till now there has been no H\( \alpha \) detection of this system. A nice example of a bow shock nebula observed in both H\( \alpha \) and X-rays is the Black Widow around PSR B1957+20 (Stappers et al., 2003). The X-ray emission of these type of bow shocks is believed to come from the shocked pulsar wind material, whereas the H\( \alpha \) emission is originating from the swept-up ISM material by the bow shock. Several hydrodynamical simulations (Bucciantini 2002; van der Swaluw et al. 2003) have been performed for these type of PWN bow shocks. Figure 4 depicts an example of such a morphology of a PWN bow shock (from Gaensler et al. 2004). The logarithmic density distribution is shown for a pulsar moving with a velocity much higher than the ISM sound speed. The separate regions in such a pulsar wind nebula bow shock can be distinguished: A/ The pulsar wind
cavity, which is elongated due to the supersonic motion of the pulsar B. The region containing the shocked pulsar wind material, part of it is forming a tail (region B1 subsonic, region B2 supersonic). C/ the swept-up ISM material by the bow shock bounding the PWN bubble. In case of the Mouse, these different areas have been identified with the X-ray map from Chandra (Gaensler et al. 2004).

4 Prospects

In recent years the amount of observational data on PWNe, due to new observational facilities has increased enormously. At the same time the rise of
relativistic magneto-hydrodynamical simulations is improving our theoretical understanding of PWNe. Future studies of PWNe will hopefully lead to a comparison between multi-wavelength studies and numerical models in order to explain the variety of morphologies observed in plerionic SNRs.

Acknowledgements. I would like to thank the participants and ISSI (International Space Science Institute, Bern) for a stimulating workshop on the “Physics of Supernova remnants in the XMM-Newton, Chandra and INTEGRAL era”, which was helpful for writing this review paper.

References

Arzoumanian, Z., Chernoff, D. F., Cordes, J. M. The Velocity Distribution of Isolated Radio Pulsars. Astrophys. J. 568, 289-301, 2002.
Begelman, M. C., Li, Z.-Y, An axisymmetric magnetohydrodynamic model for the Crab pulsar wind bubble, Astrophysical Journal, 397, 187-195, 1992
Blondin, J. M., R. A. Chevalier, and D. M. Frierson, Pulsar wind nebulae in evolved supernova remnants, Astrophys. J., 563, 806-815, 2001.
Bucciantini, N., Pulsar bow-shock nebulae. II. Hydrodynamical simulation, Astronomy and Astrophysics, 387, 1066-1073, 2002
Bucciantini, N., Blondin, J. M., Del Zanna, L., Amato, E., Spherically symmetric relativistic MHD simulations of pulsar wind nebulae in supernova remnants, Astronomy and Astrophysics, 405, 617-626, 2003
Bucciantini, N., Bandiera, R., Blondin, J. M., Amato, E., Del Zanna, L., The effects of spin-down on the structure and evolution of pulsar wind nebulae, Astronomy and Astrophysics, 422, 609-619, 2004
Chevalier, R. A., Fransson, C., Pulsar nebulae in supernovae, Astrophysical Journal, 395, 540-552, 1992
Chevalier, R. A., Young core collapse supernova remnants and their supernovae. The Astrophysical Journal, in press, astro-ph/0409013
Cioffi, D. F., McKee, C. F., Bertschinger, E. Dynamics of radiative supernova remnants. The Astrophysical Journal 334, 252-265, 1988
Del Zanna, L., Amato, E., Bucciantini, N., Axially symmetric relativistic MHD simulations of Pulsar Wind Nebulae in Supernova Remnants. On the origin of torus and jet-like features, Astronomy and Astrophysics, 421, 1063-1073, 2004
Gaensler, B. M., van der Swaluw, E., Camilo, F., Kaspi, V. M., Baganoff, F. K., Yusef-Zadeh, F., Manchester, R. N. The Mouse That Soared: High Resolution X-ray Imaging of the Pulsar-Powered Bow Shock G359.23-0.82, Astrophys. J., in press astro-ph/0312362
Gallant, Y. A., van der Swaluw, E., Kirk, J. G., Achterberg, A. Modeling Plerion Spectra and their Evolution. in Neutron Stars in Supernova Rem-
Garcia-Segura, G., Langer, N., Mac Low, M.-M. The hydrodynamic evolution of circumstellar gas around massive stars. II. The impact of the time sequence O star -> RSG -> WR star. Astronomy and Astrophysics 316, 133-146, 1996

Heger, A., Fryer, C. L., Woosley, S. E., Langer, N., Hartmann, D. H. How Massive Single Stars End Their Life. The Astrophysical Journal 591, 288-300, 2003

Hoshino, M., Arons, J., Gallant, Y. A., Langdon, A. B. Relativistic magnetosonic shock waves in synchrotron sources - Shock structure and nonthermal acceleration of positrons. Astrophys. J., 390, 454-479, 1992

Kaspi, V. M., Roberts, M. S. E., Harding, A. K. Isolated Neutron Stars. in: Compact Stellar X-ray Sources”, eds. W.H.G. Lewin and M. van der Klis, astro-ph/0402136

Komissarov, S. S., Lyubarsky, Y. E., Synchrotron nebulae created by anisotropic magnetized pulsar winds, 349, 779-792, 2004

McKee, C. F. X-Ray Emission from an Inward-Propagating Shock in Young Supernova Remnants. Astrophysical Journal, 188, 335-340, 1974

McKee, C. F., Truelove, J. K. Explosions in the interstellar medium. Physics Report 256, 157-172, 1995

Kennel, C. F., Coroniti, F. V. Confinement of the Crab pulsar’s wind by its supernova remnant, The Astrophysical Journal, 283, 694-709, 1984

Pacini, F., Salvati, M. On the Evolution of Supernova Remnants. Evolution of the Magnetic Field, Particles, Content, and Luminosity, Astrophysical Journal, 186, 249-266, 1973

Rees, M. J., and J. E. Gunn, The origin of the magnetic field and relativistic particles in the Crab Nebula, Mon. Not R. Astron. Soc., 167, 1-12, 1974.

Reynolds, S. P., Chevalier, R. A. Evolution of pulsar-driven supernova remnants. The Astrophysical Journal, 278, 630-648, 1984

Stappers, B. W., Gaensler, B. M., Kaspi, V. M., van der Klis, M., Lewin, W. H. G., An X-ray nebula associated with the millisecond pulsar B1957+20., Science, 299, 1372-1374, 2003

Truelove, J. K., McKee, C. F. Evolution of Nonradiative Supernova Remnants The Astrophysical Journal Supplement 120, 299-326, 1999

van der Swaluw, E., A. Achterberg, and Y. A. Gallant, Hydrodynamical simulations of pulsar wind nebulae in supernova remnants, Memorie della Societa Astronomia Italiana, 69, 1017-1022, 1998.

van der Swaluw, E., A. Achterberg, Y. A. Gallant, and G. Tóth, Pulsar wind nebulae in supernova remnants. Spherically symmetric hydrodynamical simulations, Astron. Astrophys., 380, 309-317, 2001.

van der Swaluw, E., A. Achterberg, Y. A. Gallant, et al, Interaction of high-velocity pulsars with supernova remnant shells, Astron. Astrophys., 397, 913-920, 2003

van der Swaluw, E., Interaction of a magnetized pulsar wind with its sur-
roundings. MHD simulations of pulsar wind nebulae, Astronomy and Astrophysics, 404, 939-947, 2003
van der Swaluw, E., Downes, T. P., Keegan, R. An evolutionary model for pulsar-driven supernova remnants. A hydrodynamical model, Astronomy and Astrophysics, 420, 937-944, 2004