Pulsar Astrophysics the Next Fifty Years
Proceedings IAU Symposium No. 337, 2017
P. Weltevrede, B.B.P. Perera, L.L. Preston & S. Sanidas, eds.

doi:10.1017/S1743921317011565

A multi-wavelength view of the pulsar environments

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Abstract. Sometimes the explosion of a supernova can generate a pulsar, most of whose rotational energy is carried away by an energetic wind of particles and magnetic fields expanding into its surroundings and eventually forming extended nebulae, i.e. the pulsar wind nebulae. The experimental advances reached in the last decades, from radio frequencies up to the highest gamma-ray energies, with instruments like VLA, VLBA, *Chandra*, *NuStar*, *Fermi*-LAT and H.E.S.S. among the others, led to the discovery of hundreds of this kind of sources allowing for population studies. In addition, this variety of high-precision spectral and morphological measurement provided an unprecedented opportunity to test and push forward the state-of-the-art theoretical models. In this contribution, we will review the latest, and most significant theoretical and experimental results.

Keywords. PWN, SNR, pulsar winds

1. Introduction

The explosion of a supernova releases almost instantaneously about 10^{51} ergs of energy, and results in an expanding blast wave, that constitutes the supernova remnant (SNR). In the case of core-collapsed supernovae, the explosion can generate a pulsar, most of whose rotational energy is carried away by an energetic wind of particles and magnetic fields expanding into its surroundings and eventually forming extended nebulae, i.e. the pulsar wind nebulae (PWN). At the early stages, PWNe are confined by the supernova ejecta, and later it can be the interstellar medium (ISM). The evolutionary stage of a PWN is not determined by the true age of the system, but rather by its dynamical age. The latter takes into account that PWNe of the same age, but expanding into very different density distributions, and/or with different spin-down luminosities, can evolve very differently. In this work we summarize the state-of-the-art understanding of the PWNe in their different evolutionary stages.

2. Young PWNe

Young PWNe are those systems that are still in the early expansion phase, during which the bubble of particles and magnetic fields is confined by the innermost slow-moving supernova ejecta and forms a shock when interacting with them. Young PWNe are characterized by a filled-center morphology. The pulsar remains located at the center of the PWN, since its kink velocity ($\sim$200-1500 km s^{-1}, Arzoumanian *et al.* 2002) is much smaller than the expansion speed, and the PWN has basically no interaction with the confining SNR. The presence of the SNR shell has, therefore, no influence on the characteristics of young PWNe, that are, instead, strongly related to the pulsar wind, and, in particular, its magnetization and energy distribution. The most studied young PWN is the Crab nebula (∼1 kyr, Buelher & Blandford 2014): the huge amount of available high-precision spectral and spatial measurements made it the best source to test our theoretical understanding. It is often considered the archetypal young PWN.

The arc-second resolution of the *Chandra* satellite (2-10 keV) allowed to resolve several young PWNe (Kargaltsev *et al.* 2015) showing that their inner regions exhibit a jet-torus structure, with the torus lying on the equatorial plane of the pulsar rotation, and the jets forming along the polar axis. Seen mainly at X-ray frequencies, these structures trace the distribution of the most energetic synchrotron-emitting electrons that have been re-accelerated at the termination shock (TS). The latter is usually associated with the inner ring detached from the torus. While the torus is believed to rise naturally as a consequence of the anisotropy of the pulsar wind flow, more energetic in the equatorial plane than along the polar axis (Del Zanna *et al.* 2004, Komissarov & Lyubarsky 2004, Bogovalov *et al.* 2005), the jets would emerge in the high-latitude post-shock region due to magnetic hoop-stress, and can be bended because of kink instabilities (Begelman 1998). Additionally, the torus is highly dynamical showing series of rings, arcs, ripples moving outwards with variable positions and luminosities. These substructures are usually dubbed as wisps (Scargle 1969, Hester *et al.* 1996, Bietenholz *et al.* 1997, Weisskopf *et al.* 2000). Young PWNe are characterized by flat radio spectra ($\alpha < 0.3$ Kothes 2017) that steepens between radio and optical frequencies. The nature of these spectral breaks is still under debate, sometimes interpreted as an intrinsic feature of the parent population, sometimes as the signature of the cooling losses (Bock & Gaensler 2005). In the specific case of the Crab nebula, the uncooled radio electrons are considered as a separate synchrotron component (Bandiera *et al.* 2002, Temim *et al.* 2006), but it is not yet clear if they are continuously injected as part of the pulsar wind, or the result of particle acceleration somewhere else, although surely not a relic population (Olmi *et al.* 2015).

The capability to reproduce the vast variety of details observed in the Crab Nebula inner region, both in terms of morphology, brightness variability, and polarization, signed the success of the 2-dimension relativistic magneto-hydrodynamic (MHD) simulations (Bucciantini *et al.* 2005, Del Zanna *et al.* 2006, Olmi *et al.* 2014). In fact, most of the detected features could be explained as a combination of Doppler boosting and flow dynamics effects. However, these models provide good representation only of the 1/5 innermost region of the Crab nebula (Olmi *et al.* 2016), where the toroidal magnetic field approximation still holds. This assumption is relaxed at increasing distances from the pulsar though: a more isotropic B-field is required to properly account for the X-ray brightness contrast between the inner ring and the torus of the Crab nebula. The main problem of the 2D MHD models is related to the required low magnetization of the pulsar wind at the TS (σ >0.01, with σ being the ratio between the magnetic and the kinetic energy flux), thus the low averaged B-field strength across the nebula. On one hand this requires a strong magnetic dissipation to happen before the TS (the so-called σ-problem), and, on the other hand, it asks for a huge amount of synchrotron-emitting electrons, that in turn results on the overestimation of the inverse Compton component emission by three orders of magnitude (Volpi *et al.* 2008).

The best way to study the large-scale magnetic field structure is to study either synchrotron radio or gamma-ray inverse Compton emission, that are both integrated over the lifetime of the PWN. In particular, radio polarimetry is one of the most powerful tools in this respect (Kothes 2017 for a review). Unfortunately there is no common general picture, with a huge diversity of complex and distinct structures, although at the edges of the nebula the magnetic field is often radial (Reich *et al.* 1998). On the other hand, morphological studies in the gamma-ray energy band cannot play any significant role since young PWNe are barely resolved by imaging Cherenkov telescopes. The H.E.S.S. collaboration has recently published the detection of the Crab Nebula extension of less than one arc-minute above 1 TeV though (Holler *et al.* 2017). Spectral measurements of the inverse Compton component by PWNe can instead provide significant insights on the large-scale magnetic field strength and structure (Meyer *et al.* 2010, Martin *et al.* 2012), as shown, for instance, by the Crab high-precision results by the MAGIC collaboration that can definitely reject a constant B-field across the nebula (MAGIC coll. 2015).

The long-standing σ-problem moved a step-froward in its possible solution in the last few years thanks to the first 3D MHD simulations (Porth *et al.* 2013) that allow for a much higher magnetization of the pulsar wind at the TS ($\sigma \sim 1$). By increasing the dimensionality of the simulations, the kink instabilities are properly accounted, resulting in a strong reduction of the artificial compression of the B-field around the polar axis. 3D MHD simulations are very computationally expensive, so that they were, at the moment, run only for at maximum 200 yr (Olmi *et al.* 2016), and already at this early stage,they show a too-high magnetic dissipation (Porth *et al.* 2014), which, however, seems to become less important after 100 yr (Olmi *et al.* 2016). In addition, this new view of a highly magnetized wind at the TS support the new interpretation of the particle acceleration at the TS according to which two different mechanisms are at work: Fermi I-like and magnetic reconnection, with the first being more efficient in the narrow equatorial sector where the magnetization is sufficiently low ($\sigma < 10^{-3}$, Sironi & Spitkovosky 2009), and the second elsewhere. Olmi *et al.* (2015) suggests that Fermi I-like mechanism is responsible for the acceleration of the optical/X-ray-emitting electrons with a spectral index around 2, whereas magnetic reconnection that can account for harder spectra (Sironi *et al.* 2011) would be accelerating the radio electrons having a spectral index of 1.5. The idea of having distinct acceleration regions along the TS for different particle populations is corroborated by the spatial non-coincidence of the wisps at radio, optical and X-ray frequencies (Bietenholz *et al.* 2004, Schweizer *et al.* 2013). In addition, there might be compact regions (with sizes corresponding to those of the variable sub-structures visible in optical and X-rays) close to the TS where fast magnetic reconnection occurs (Cerutti *et al.* 2013, Lyutikov *et al.* 2016). This picture is invoked to explain the unexpected discovery of the Crab synchrotron nebula flares above 100 MeV (Tavani *et al.* 2011, LAT coll. 2011) that can exhibit a flux doubling in less than 8 hrs with hard spectra (photon index 1.3) exceeding the synchrotron critical energy (Buelher & Blandford 2014). So far 11 flares have been recorded by the two gamma-ray satellites, with a rate of $\sim$1 per year. However, the orphanhood of these flares, i.e. no counterpart found at any different wavelength (Weisskopf *et al.* 2013, Rudy *et al.* 2015, Bietenholz *et al.* 2015), has prevented from nailing down their emission location.

Post-shocked particles propagate either via diffusion or advection. Both mechanisms predict a shrinking of the nebular size at increasing photon energies due to higher-energy photons dying out sooner than the lower-energy one. Still the spectral steepening as a function of the distance from the pulsar follows different behaviors in the two distinct cases: whereas diffusion foresees a linear steepening, advection predicts that the photon index remains constant throughout the source with a sudden steepening at its edge. This makes the spatial-dependent spectroscopy one of the most powerful tools to study the particle transport mechanism, now at the reach also in the X-ray energy band thanks to the *NuStar* satellite. The recent discovery of spatially variable rate shrinking, more rapid in the jet/counter-jet direction than in the equatorial plane (Madsen *et al.* 2015) suggests that a combination of diffusion and advection is at work

https://doi.org/10.1017/S1743921317011565 Published online by Cambridge University Press

(Tang & Chevalier 2012), being the first dominant along the jet, and the second in the torus.

3. Middle-aged PWNe

The SNR blast wave move supersonically into the ISM forming the forward SNR shock (FS). As this shock sweeps up an increasing amount of material, i.e. the SNR shell, the FS decelerates with the supernova ejecta catching up, hence driving a reverse shock (RS). The latter moves back towards the center of the SNR and heats up the gas enriched with heavy elements from the SN explosion. If the ISM around the SNR is non-uniform, the FS expands more rapidly into the regions of lower density.

We define here as middle-aged PWNe, those systems that have already interacted with the reverse shock. When crashing, the PWN is disrupted and displaced in the direction of the ISM regions with the lowest density, eventually leaving behind relic nebulae (Blodin *et al.* 2001, van der Swaluw *et al.* 2001, Gelfand *et al.* 2009). The PWN/RS interface is subject to Rayleigh-Taylor instabilities that lead to the formation of filamentary structures where the dense ejecta material is mixed into the relativistic fluid. A nice example of a crushed PWN is provided by the snail nebula (G327.1-1.1, 11-29 kyr, Temim *et al.* 2015): at radio frequencies it shows a relic nebula in the interior, to the south-west, of the containing SNR and it is accompanied by a finger-like structure extending towards the pulsar. The pulsar cometary tail, seen also at X-ray frequencies, is interpreted as the combination of the PWN/RS interaction and the pulsar motion. A completely different morphology is seen in the Vela X PWN. It shows a $2^{\circ} \times 3^{\circ}$ extended radio nebula, that spatially correlates with emission in the GeV energy band, and a much more compact X-ray/TeV emission that extends south to the pulsar along a prominent filament. This latter feature, dubbed as cocoon, is interpreted as a recent PWN created after the crash with the RS (Blodin *et al.* 2001) and still containing uncooled electrons, as shown by the lack of spectral variations in this region (H.E.S.S. coll. 2012a, Tibaldo *et al.* 2017). The non-detection of the extended radio nebula at TeV energies provides evidence for particle escape (Hinton *et al.* 2011). Recent results from MSH 15-52 may point towards a similar case (Tsirou *et al.* 2017).

Middle-aged PWNe are the most common class of gamma-ray emitters in the TeV sky (Donath *et al.* 2016). This is strictly related to the evolution of the ratio between the the synchrotron and the inverse Compton efficiencies: the decrease of the B-field strength associated with the adiabatic expansion of the PWN causes a decrease of the synchrotron efficiency making the inverse Compton the dominant emission component (Torres *et al.* 2014). However, after the PWN interaction with the RS, the B-field strength increases because of the new compression, and so does the synchrotron emission until further re-expansion when the initial behavior is restored (Gaensler & Slane). Gamma-ray observations provide a unique tool to study these objects, often associated with much fainter nebulae at lower energies. Mainly thanks to the success of the current generation of imaging Cherenkov telescopes, population studies at TeV energies are finally at the reach (H.E.S.S. coll. 2017) and cooling signatures could be detected also at these energies (H.E.S.S. coll. 2006, H.E.S.S. coll. 2012b). In addition, extension measurements of TeV PWNe can shed some light on the propagation mechanism at work. An extension of $\sim$100 pc, as in the case of HESS J1825-137 (Mitchell *et al.* 2017), can be explained only if rapid diffusion of the associated electrons is taken into account (van Etten & Romani 2011). This result would support the idea that diffusion could be the dominating mechanism in old PWNe (Tang & Chevalier 2012, Porth *et al.* 2016).

4. Supersonic PWNe

While the pulsar keeps moving with its motion speed, the SNR expansion slows down with time ($\propto t^{2/5}$ and $\propto t^{3/10}$ in the Sedov and pressure-driven phase), so eventually after 20-200 kyr the pulsar leaves the SNR. The subsequent supersonic motion of the pulsar changes dramatically the morphology of the PWN: since the ram pressure exceeds the ambient pressure, the PWN acquires a cometary shape with the head around the pulsar and a long tail behind it (Reynolds *et al.* 2017, Kargaltsev *et al.* 2017 for recent reviews). These synchrotron-emitting tails, that extend up to tens of pc, show the expected size shrinking at increasing emission wavelengths and spectral softening with increasing distance from the pulsar (Pavan *et al.* 2016, Reynolds *et al.* 2017). However, very recently, Kargaltsev (2017) showed at least two PWN, i.e. J1509-5850 and B0355+54, show no cooling tread, but rather a spectral hardening with increasing distance from the pulsar. This result could be interpreted as a possible particle re-acceleration in-situ: a more twisted B-field further away from the pulsar would favor magnetic reconnection. These supersonic PWNe are often embedded in IR-optical-UV bow-shock nebulae, formed by the surrounding medium shocked in the forward shock (Brownsberger & Romani 2014).

One of the most intriguing puzzles about the supersonic PWNe are their misaligned outflows, i.e. outflows emerging almost perpendicularly to the pulsar motion, hence to the PWN tail. They have been suggested as strong jets misaligned with the velocity vector, or as the result of the leaking of high-energy particles from the apex of the bow nebula (Bandiera 2008). Both these interpretations have been already challenged by recent observations though. In the first case one would expect a bending that it is not observed up to tens-of-parsec scales (Dolch *et al.* 2016), in the second case no asymmetry is expected in contrast to what seen in the Lighthouse nebula (Pavan *et al.* 2016). In addition, the 11 pc outflow of Lighthouse nebula exhibits a bending around the pulsar that rejects the high-energy particle leaking scenario. Among this class of bizarre supersonic PWNe, Geminga is certainly the oddest example with its three tails (Caraveo *et al.* 2003, Posselt *et al.* 2016) whose nature is not certain yet. One could assume that the lateral tails are bended jets, whereas the smaller central one is the crashed torus. Alternatively, the lateral tails can be considered as a limb-brightened shell and the central one the usual jet, but only future X-ray imaging polarimetry can help disentangling the two scenarios.

These supersonic PWNe appear to be very inefficient inverse Compton emitters. So far the only one detected in gamma ray is Geminga, seen at TeV energies by the HAWC collaboration with a 5° extension (Salesa *et al.* 2017).

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