Plerions and Pulsar-Powered Nebulae

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Abstract.
In this brief review, I discuss recent developments in the study of pulsar-powered nebulae ("plerions"). The large volume of data which has been acquired in recent years reveals a diverse range of observational properties, demonstrating how differing environmental and pulsar properties manifest themselves in the resulting nebulae.

INTRODUCTION
All isolated pulsars have steadily increasing periods. However, only a very small fraction of the corresponding spin-down luminosity, \( \dot{E} \equiv 4\pi^2 I \dot{P}/P^3 \) (where \( P \) is the pulsar spin period and \( I \) is the pulsar’s moment of inertia), can usually be accounted for by the pulsations themselves. It is rather assumed that most of this rotational energy is converted into a relativistic wind.

At some distance from the pulsar, the wind pressure and confining pressure balance, producing a shock at which relativistic particles in the wind are accelerated and have their pitch angles randomized. These particles consequently radiate synchrotron emission, generating an observable pulsar-powered nebula, or “plerion”\(^2\). Plerions can be powerful probes of a pulsar’s interaction with its surroundings — their properties can be used to infer the geometry, energetics and composition of the pulsar wind, the space velocity of the pulsar itself, and the properties of the ambient medium. Furthermore, the mere existence of a plerion indicates the presence of a pulsar within, even when the latter has not yet been directly detected.

In the following discussion, I briefly review our historical and theoretical understanding of plerions, and describe some of the highlights from recent work. There have been many recent developments in this field, and space precludes me from providing a more comprehensive review. I refer the reader to preceding reviews on plerions and their pulsars by Slane et al [1], Chevalier [2], Frail [3,4] and Gaensler [5].

\(^1\) Hubble Fellow
\(^2\) For simplicity, I will use the term “plerion” to refer generically to all forms of pulsar nebulae, and will make specific distinctions when I refer to particular sub-categories of object.
HISTORICAL OVERVIEW

Any discussion of plerions and pulsar wind nebulae must of course begin with the Crab Nebula. While it has long been realized that the Crab Nebula is the product of a supernova explosion [6], its filled-center morphology, flat radio spectrum and high fraction of linear polarization all indicate that it is a very different source from “shell-type” supernova remnants (SNRs) like Cassiopeia A and the Cygnus Loop. A pulsar was discovered embedded in the Crab Nebula in 1968 [7], and it is the continual injection of energy into the nebula by this source which is believed to produce the Crab’s unusual properties.

In the early 1970s, it was suggested that the filled-center SNR 3C 58 was similarly powered by an (as yet unseen) pulsar [8]. Before long, several other such sources were identified, and a whole class of “Crab-like” SNRs began to emerge [9–11]. Weiler & Panagia [10] proposed the name “plerion” for such sources, from the Greek “πληρης” meaning “full”.3

Milne et al [13] introduced an additional complication, when they pointed out that the SNR MSH 15–56, while having a limb-brightened radio shell like most SNRs, also contains a central core which otherwise resembles a plerion (see Figure 1). They termed this source a “composite” SNR, and proposed that it combined the properties of shell-type SNRs and of plerions.

In the last 20 years, this simple classification of SNRs into shells, plerions and composites has largely remained unchanged. In Green’s most recent Galactic SNR Catalog [14], 225 SNRs are listed, of which 23 are composites and nine are plerions. Of these 32 remnants which are presumed to be powered by a pulsar, the central pulsars have now been detected in ten, while a further five contain central X-ray point sources believed to be associated neutron stars. Adding to this list two pulsar nebulae in the LMC in which pulsars have been detected, we have thus now identified the central source in 50% of SNRs with plerionic components. The premise that plerions are powered by pulsars therefore remains essentially unchallenged.

OBSERVATIONAL PROPERTIES

At radio wavelengths, plerions (and plerionic components of composite SNRs) generally have an amorphous filled-center morphology, with a flat spectrum (−0.3 ≤ α ≤ 0, $S_\nu \propto \nu^\alpha$) and a high degree of linear polarization. In cases where an associated pulsar has been identified, it is not necessarily near the center and/or brightest part of the plerion. Kothes [15] has proposed that the radio luminosity of a plerion, $L_R$, the diameter of the plerion, $D$, and $\dot{E}$, approximately follow the relation $L_R \propto \dot{E}D$.

3) Shakeshaft [12] has pointed out that “πληρης” is not a Greek word, and that “plethoric supernova remnant” would be a more linguistically-correct term to describe these objects. However, this advice does not seem to have been heeded by the community!
Figure 1. The composite SNRs MSH 15–56 (left) and G327.1–1.1 (right). The greyscale shows the 843 MHz radio emission from each remnant [16], demonstrating their composite morphologies. The contours delineate X-ray emission as seen by ASCA SIS [17,18], and show the smaller extent and offset of the X-ray plerions with respect to their radio counterparts.

In the X-ray regime, plerions imaged at sufficient spatial resolution seem to contain axially-symmetric structures such as tori and jets. Plerions generally have smaller X-ray extents than they do in the radio (see Figure 1), presumed to be the result of the shorter lifetimes of synchrotron-emitting electrons at progressively higher energies. For the same reason, the spectrum of plerions in X-rays is steeper ($\alpha \sim -1$) than in the radio, and any associated pulsar is usually coincident with the brightest X-ray emission. Various efforts have been to look for correlations between $\dot{E}$ and the corresponding plerion’s X-ray luminosity, $L_X$. These studies consistently suggest that these two quantities are correlated, showing that $L_X \propto \dot{E}^a$ with an exponent in the range $1 \lesssim a \lesssim 1.4$ [19,20].

A PLETHORA OF PLERIONS

While we assume that all plerions are “Crab-like” in that they are similarly powered by pulsars, in most respects other plerions have very different properties to the Crab Nebula. Indeed, on looking through the available sample, it becomes apparent that plerions form a very heterogeneous set of objects. Without wanting to suggest any definitive categories\(^4\), some of the different types of object include:

- “Standard” composites, in which the plerionic component contains a detected pulsar and is surrounded by a shell. The SNR 0540–69.3 in the LMC [21] is a good example of such a source.

\(^4\) See Chevalier [2] for a suggested evolutionary sequence for some of these categories.
• “Naked” plerions, typified by the Crab Nebula, in which no surrounding SNR shell can be seen. In the case of the Crab itself, a good argument can be made that that a SNR blast-wave is present, but that it simply can’t be seen [22]. However, Wallace et al [23,24] have shown that some of these “naked” plerions are interacting directly with the ambient ISM, and have argued that such sources are produced by low-energy explosions in which no fast-moving ejecta are produced.

• “Bow-shock” plerions such as those associated with PSRs B1853+01 and B1757–24 [25,26]. These nebulae have a cometary morphology resulting from their pulsar’s high space-velocity.

• “Radio-quiet” plerions such as MSH 15–5 and CTA 1 [27,28]. In these cases, a pulsars powers a nebula which is prominent in X-rays but is not seen at radio wavelengths. It has been proposed that these plerions are produced by pulsars with high magnetic fields, $B \gtrsim 10^{13}$ G [29,30]. Such plerions suffer severe adiabatic losses early in their lives, and so are radio-bright only at the earliest stages of their evolution.

• “Hyper-plerions”, such as G328.4+0.2 and N 157B, have very large diameters ($\lesssim 20$ pc) and radio luminosities higher than that of the Crab Nebula [31,32]. These plerions appear to be powered by a low field pulsar, $B \lesssim 10^{12}$ G, which generates a large and long-lived ($\sim 10$ kyr) radio nebula [31].

• “Interacting composites”, typified by CTB 80, in which a high-velocity pulsar catches up with and re-energizes its associated shell SNR [33].

• “Low frequency spectral break” plerions, such as 3C 58 and G21.5–0.9. These plerions show a sudden steepening of their spectra at radio or millimeter frequencies, thought to be caused by a “phase change” in the pulsar’s energy output [34]. These sources will be discussed further below.

PLERION EVOLUTION

A “standard” model of evolution has emerged in which a plerion is modeled as a spherically symmetric expanding synchrotron bubble for which (in the simplest case) equipartition is assumed between particles and magnetic fields in the nebula [35,36]. The only source of energy input into the nebula is the spin-down of the pulsar, whose time-evolution is described by:

$$\dot{E} = \frac{L_0}{(1 + t/\tau_0)^p}, \quad p = \frac{n + 1}{n - 1}$$

where $L_0$ is the pulsar’s initial spin-down luminosity, $\tau_0$ is some characteristic time-scale (typically a few hundred years) and $n$ is the pulsar’s braking index.

For times
At times $t < \tau_0$, the pulsar’s rate of output is approximately constant, $\dot{E} \approx L_0$. At times $t > \tau_0$, the spin-down luminosity decays as a power-law, $\dot{E} \propto t^{-p}$.

Competing against this injection are two sources of energy loss: adiabatic losses due to expansion of the nebula, and synchrotron losses. Including all these terms, one can derive expressions for the evolution of the particle content, magnetic field, luminosity and spectrum in each phase of evolution. For $t < \tau_0$, a single break is seen in the plerion’s spectrum, corresponding to the frequency at which synchrotron losses dominate at time $t$. At times $t > \tau_0$, this original spectral break moves to higher frequencies as the nebular magnetic field decays, while a second “fossil” break, resulting from the rapid decay of $\dot{E}$ beginning at $t = \tau_0$, appears at lower frequencies [35]. When modeling the evolution of a plerion, the presence of a surrounding shell-type SNR, and/or the actual detection of the associated pulsar, allows one to estimate the nebular magnetic field strength, the rate of energy input by the pulsar and the age of the system. The properties of the SNR, pulsar and plerion can then be used to jointly constrain the parameters of the system [1].

While this picture can explain the basic properties of the Crab Nebula and other plerions, there have been many subsequent refinements to take into account particular situations and details of the nebular physics. To conclude this section, I list below some of the recent work that has been carried out on plerion evolution, and discuss some of the more interesting developments in more detail.

- Amato et al [37] have taken into account the fact that the particle distribution within a plerion is not homogeneous, and develop a model in which synchrotron-emitting particles propagate away from the pulsar.
- van der Swaluw et al [38] have considered the interaction which occurs when a pulsar catches up with and penetrates its associated shell SNR.
- Luz & Berry [39] have modeled the interaction between a plerion and its surrounding shell SNR.
- Wilkin [40] has developed a detailed treatment of bow-shocks produced by anisotropic winds, as are likely to be produced by pulsars.
- Chevalier [2] has pointed out that the reverse shock produced by a SNR blast-wave will reach the center of the SNR in $\sim 10^4$ yr. This can compress, brighten and distort a central plerion, and could account for the filamentary appearance and offset of the pulsar from the center of the plerion seen in Vela X.
- Chevalier [41] has also recently developed a simplified one-zone model for the X-ray emission from a plerion. He derives an analytic expression for the emission, so that the X-ray luminosity, $L_X$, depends only on the spin-down luminosity of the pulsar ($\dot{E}$), the photon index of the nebula ($\Gamma$), the wind magnetization parameter ($\sigma$), the Lorentz factor of the wind ($\gamma_w$) and the radius of the shock ($r_s$). This model successfully predicts the ratio $L_x/\dot{E}$ for most plerions in which pulsars have been detected.
Various authors have considered plerions such as 3C 58, which have low-frequency spectral breaks [34,42,43]. These plerions are characterized by sharp spectral breaks ($\Delta \alpha \sim 0.8 - 1.0$) at frequencies $\nu_b \lesssim 50$ GHz, in sharp contrast to the $\Delta \alpha = 0.5$ break seen for the Crab Nebula in the infrared. The spectral breaks seen in these other plerions cannot be due to synchrotron losses, as the inferred magnetic field is so high that the energy in magnetic fields would then be larger than the kinetic energy of the plerion. Woltjer et al [34] show that a plerion powered by a pulsar with a low braking index ($n \ll 3$) can produce a low-frequency fossil break at times $t > \tau_0$, but that this break is not sharp enough to match observations. They instead consider a model in which there is a sudden “phase change” in the pulsar’s energy output, when perhaps the pulsar’s wind suddenly becomes magnetically dominated. In such a system a sharp low-frequency spectral break is indeed predicted. Such a model can also account for the low X-ray luminosity of 3C 58, and for the fact that its radio flux is increasing with time (rather than decreasing in the case of the Crab). While these arguments make a strong case that the central sources in these low-frequency break plerions are quite different from the Crab Pulsar$^5$, the only definitive resolution to this puzzle will be to actually detect their central sources.

NEW RESULTS

Gamma rays: It has long been thought that many of the unidentified $\gamma$-ray sources in the Galactic Plane correspond to young high-$\dot{E}$ pulsars and their associated plerions. Indeed, Halpern et al [44] have identified a new radio source, G106.6+3.0, which is coincident with the otherwise unidentified EGRET source 3EG J2227+6122 and also with the X-ray source AX J2229.0+6114. This radio source is polarized, has a flat spectral index, and has a possible bow-shock morphology. The properties of G106.3+3.0 all suggest that this source is a plerion powered by a pulsar with $\dot{E} \gtrsim 10^{36}$ erg s$^{-1}$. Other possible plerions associated with $\gamma$-ray sources have been reported by Roberts et al [45] and Oka et al [46].

Radio: Stappers & Gaensler have carried out an extensive search for radio nebulae associated with radio pulsars [47–49]. Of 31 pulsars observed, only one new pulsar nebula was found, indicating that pulsars reside predominantly in low-density environments. Meanwhile, the Australia Telescope Compact Array continues to image various plerions at high spatial resolution, highlighting the diversity of plerion properties and morphologies [31,32,50].

Optical: The morphology of an optical bow-shock around a pulsar contains a great deal of information about a pulsar’s interaction with the ISM. Imaging and spectroscopy of such bow-shocks around PSRs B2224+65 (“the Guitar Nebula”)

$^5$ For a different interpretation in terms of central pulsars with high magnetic fields, see the discussion by Frail [4].
and J0437–4715 have resulted in determinations of the 3D space velocities of these pulsars, and the densities and ionization fractions of their environments [51,52].

**X-rays:** *ASCA* observations of various pulsars and their plerions have recently been re-analyzed. Contrary to previous claims [53], there now seems to be no plerions apparent around PSRs B1610–50, B1055–52, B0656+14 or Geminga [49,54,55]. PSR B1046–58 has no extended plerion, but may be associated with a compact X-ray nebula [55].

With the recent launch of *XMM* and *Chandra*, it is unsurprising that there are many new results on pulsars and their nebulae. The high-resolution of *Chandra* has been brought to bear on the two prominent plerions in the Large Magellanic Cloud, SNRs 0540–693 and N 157B. X-ray data on the former suggest a possible Crab-like morphology with the hint of jets and a torus [56,57], while observations of the latter appear to confirm the cometary morphology for this nebula seen in *ROSAT* data [58].

The *Chandra* image of the Vela Pulsar is spectacular (Figure 2; [59]). The surrounding nebula is remarkably similar to the Crab, showing clear evidence for equatorial rings and axial jets, and appearing to rule out earlier interpretations of this system as a bow-shock. The orientation of the pulsar’s proper motion, the pulsar’s spin axis and the direction of outflow along the X-ray jets all seem to align. This alignment is similar to that seen for the Crab Pulsar, and provides important constraints on the origins of pulsar spin periods and space velocities [60,61]. Helfand et al [59] note that the X-ray properties of the Vela plerions suggest a magnetization parameter $\sigma \approx 1$, in sharp contrast to the Crab Nebula for which $\sigma \approx 3 \times 10^{-3}$.

Finally, *Chandra* and *XMM* observations of the plerion G21.5–0.9 have revealed both a compact central source and a surrounding halo (Figure 2). The central source is resolved by *Chandra*, and may be a wisp or termination shock which is hiding the pulsar itself [62]. Meanwhile, *XMM* observations clearly demonstrate that the surrounding halo has a power-law spectrum, and that this spectrum steadily steepens with radius [63]. It is not yet clear whether the plerion is much larger than previously thought, or if the halo is a surrounding SNR blast-wave so that G21.5–0.9 should be re-classified as a composite SNR. Deep radio observations of this source will be required to distinguish between these possibilities.

**CONCLUSIONS**

With the high-quality data now available across the spectrum, it has become abundantly apparent that the Crab Nebula is not typical of plerions. The large diversity in the observed and inferred properties of plerions appears to result from differences in their environments, ages and associated pulsars. Key to understanding this variety seems to be better modeling of the interaction of plerions and pulsars with their surrounding SNRs.

It is also clear that many plerions are still waiting to be discovered. Approximately 20% of Galactic radio SNRs are yet to be imaged with a spatial resolution of
FIGURE 2. The Vela Pulsar and surrounds (left) and SNR G21.5–0.9 (right). The image of the Vela Pulsar was produced from archival Chandra HRC data, and has been convolved with a 0.5′′ gaussian (see also [59]). G21.5–0.9 was observed with XMM EPIC MOS [63] — the contours show 1.4 GHz radio emission from the plerion indicating its previously-known extent, while the greyscale has been scaled logarithmically to show the faint surrounding X-ray halo.

better than ∼ 10 beams across their diameter, and imaging these SNRs at higher resolution could reveal central pulsar-powered components. Furthermore, many pulsar nebula are seen in hard X-rays but not at radio wavelengths, and so many apparently shell-type SNRs which have not yet been observed at higher energies may also harbor a central plerion.

A glance at the list of targets approved for Chandra and XMM shows that many plerions have been or are about to be observed with these new instruments. These data will obviously produce a great deal more information on some of the issues touched on here. Do all pulsar winds show a “torus + jets” morphology? Is the alignment between rotation axis and proper motion seen for the Crab and Vela pulsars a common characteristic? Do anomalous X-ray pulsars and soft γ-ray pulsars power associated nebula? Do “naked” plerions have faint surrounding shells? We can look forward to a whole new picture of plerions emerging in the near future.

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