PULSAR WIND NEBULAE: THEORETICAL ASPECTS AND
OBSERVATIONAL CONSTRAINTS

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ABSTRACT

Of the known pulsar wind nebulae, 8 are good candidates for being in the early stage of evolution where the wind
nebula is interacting with the freely expanding supernova ejecta. Several of these have been identified with historical
supernovae. Although the identification of SN 1181 with 3C 58 has been thought to be relatively secure, the large size
of the nebula, the amount of swept up mass, and the internal energy indicate a larger age. For G11.2–0.3, the nebular
size and internal energy are consistent with the identification with the possible supernova of 386. Although the Crab
Nebula appears to have approximate energy equipartition between particles and the magnetic field, the nebulae 3C
58 and MSH 15–52 appear to be particle dominated. The low magnetic field is consistent with models in which the
nebulae are created by a shocked pulsar wind.

INTRODUCTION

Pulsars are expected to be born inside the supernova explosions of massive stars, which provide the surroundings
for the initial evolution of their wind nebulae (Reynolds and Chevalier, 1984). The PWNe (pulsar wind nebulae)
initially expand in the freely expanding ejecta of the supernova. Eventually, the reverse shock wave from the supernova
interaction with the surrounding medium makes its way back to the center where it can crush the PWN. This later
phase of evolution has recently been the subject of detailed studies (van der Swaluw et al., 2001; Blondin et al., 2001).
In particular, Blondin et al. (2001) noted that the reverse shock is likely to be asymmetric so that the PWN can be
displaced from its position over the pulsar. This scenario provides an explanation for the displacement of the radio
emitting PWN in the Vela remnant (Bock et al., 1998) and other remnants.

Here, I emphasize PWNe that are likely to be in the earlier phase of evolution, before the reverse shock effects.
Recent discoveries at X-ray and radio wavelengths have substantially increased the number of such objects. In § 2,
the possible members of this class are listed. For objects with an approximately constant pulsar power, the expansion
in a supernova is treated in § 3. Constraints implied by the energy in the nebulae are discussed in § 4. The conclusions
are in § 5.

YOUNG PULSAR WIND NEBULAE

A list of probable young PWNe in which central pulsars have been identified is given in Table 1; these objects
are plausibly interacting with ejecta. The second column gives the observed pulsar period, P, and the third column
gives the characteristic pulsar age, \( t_{ch} = P/2\dot{P} \). If the pulsar is born rotating much more rapidly than the current
rate and the braking index is \( n = 3 \), then \( t_{ch} \) is the actual age. If the pulsar is born with a period close to its current
period, it can be younger than \( t_{ch} \). Alternatively, if the pulsar is born spinning rapidly and has a braking index \( n < 3 \),
it can be older than \( t_{ch} \). The fourth column is an estimate of the actual age. For 0540–69 (Kirshner et al., 1989)
and G292.0+1.8 (Murdin and Clark, 1979), the age estimate is from the size of the nebula and velocities found from
optical spectroscopy. For the other objects with ages, the estimate is from a tentative supernova identification, given
Table 1. Young pulsars/pulsar wind nebulae

| Object       | $P$ (msec) | $P/2 \dot{P}$ (year) | Age (year) | SN | SNR | Swept up ejecta? | Refs. |
|--------------|------------|----------------------|------------|----|-----|------------------|-------|
| 0540–69      | 50         | 1660                 | 760        | Yes | Yes | optical          | 1     |
| 3C 58        | 66         | 5390                 | 821        | Yes | 1181| X-ray            | 2     |
| Crab         | 33         | 1240                 | 948        | 1054| Yes | optical          | 3     |
| Kes 75       | 325        | 723                  | Yes        |     |     |                  | 4     |
| G292.0+1.8   | 135        | 2890                 | $\leq 1600$ | Yes |     | Maybe optical    | 5,6   |
| G11.2–0.3    | 65         | 24,000               | 1616       | 386 | Yes |                  | 7     |
| MSH 15–52    | 150        | 1700                 | 1817       | 185 | Yes |                  | 8     |
| G54.1+0.3    | 137        | 2890                 |            |    |     |                  | 9,10  |

References: (1) Kirshner et al. (1989); (2) Bocchino et al. (2001); (3) Sankrit and Hester (1997); (4) Helfand et al. (2003); (5) Camilo et al. (2002b); (6) Hughes et al. (2001); (7) Roberts et al. (2002); (8) Gaensler et al. (2001); (9) Lu et al. (2002); (10) Camilo et al. (2002a).

in the next column. The identification of the Crab with SN 1054 is generally considered very secure, but the other identifications are less secure. There is still some uncertainty over whether all of the events are in fact supernovae, e.g., SN 386 (Stephenson and Green, 2002). The next column indicates whether an extended supernova remnant is observed around the PWN, and the penultimate column indicates whether there is evidence for ejecta swept up by the PWN.

There are indications that these nebulae are in the early phase of interaction with freely expanding ejecta. One expectation in this picture is that the PWN should shock and sweep up a shell of supernova ejecta (Reynolds and Chevalier, 1984). The shock wave is initially expected to be radiative, but it becomes nonradiative due to the decline in the supernova density. A good example of an ejecta shell is the complex of filaments in the Crab Nebula. In this case, there is evidence for the shock wave in the ejecta (Sankrit and Hester, 1997); it may be in the process of making a transition from radiative to nonradiative. For 3C 58, there is evidence for X-ray emission from swept-up ejecta (Bocchino et al., 2001), implying the presence of a nonradiative shock. The optical emission from 0540–69 may be from a radiative shock (Kirshner et al., 1989). The optical emission from G292.0+1.8 appears to be from the vicinity of the PWN (Murdin and Clark, 1979), but the relation between them has not yet been determined.

Another expectation of the model with expansion in ejecta is that the pulsar should be centrally located within the PWN. This appears to be true for the objects listed in Table 1, although in most cases the PWN has an asymmetric boundary. The PWN in G292.0+1.8 is substantially off the center of the surrounding supernova remnant, which has led to the suggestion that the pulsar has a velocity $\sim 770 \text{ km s}^{-1}$ (Hughes et al., 2001). If this is the case, the pulsar is expected to move to a place in the ejecta where it is comoving with the surrounding gas and it is surrounded by uniformly expanding ejecta. Some degree of asymmetry may develop if there is a gradient in the surrounding density distribution.

MODELS FOR 3C 58 AND G11.2–0.3

If we assume that 3C 58 and G11.2–0.3 are associated with SN 1181 and SN 386, respectively, models for the PWNe can make use of the fact that the characteristic age is much larger than the true age, so that the pulsars have not significantly spun down. This allows the assumption that the pulsar power, $\dot{E}$, is constant during the evolution.

We begin by considering the expansion of the PWN into the inner parts of the supernova ejecta. The density distribution into which the PWN initially expands can be estimated from explosion models. Chevalier and Fransson (1992) used simple power law models for the density distribution. More detailed models have been considered by Matzner and McKee (1999) who give asymptotic forms for the final density distribution at low and high velocities. For the cases to be studied here, the asymptotic low velocity density profile is applicable over the time of interest. For an explosion in a star with
a radiative envelope, the inner density profile, using eq. (46) of Matzner and McKee (1999), can be expressed as

$$\rho \sim 4.3 \times 10^5 \left(\frac{v}{1000 \text{ km s}^{-1}}\right)^{-1.06} \left(\frac{M_{ej}}{10 M_\odot}\right)^{1.97} E_{51}^{-0.97} \text{ g cm}^{-3} \text{ s}^3,$$

where $v = r/t$ is the free expansion velocity, $M_{ej}$ is the total ejected mass, and $E_{51}$ is the explosion energy in units of $10^{51}$ ergs. For a star with a convective envelope, the density distribution may be flatter, but the density at 1000 km s$^{-1}$ is close to the above value.

The expansion of a PWN in a density distribution can be approximately treated as a thin shell driven by a uniform pressure wind bubble with adiabatic index $\gamma = 4/3$ (Ostriker and Gunn, 1971; Chevalier, 1977; Reynolds and Chevalier, 1984). The radius can be found analytically if the pulsar power, $\dot{E}$, is constant and the surrounding medium has a power law density distribution. As discussed above, this may be the case for 3C58 and G11.2–0.3. Then, from eq. (2.6) of Chevalier and Fransson (1992), we have

$$R_p = 0.59 \dot{E}_{38}^{0.254} E_{51}^{0.246} \left(\frac{M_{ej}}{10 M_\odot}\right)^{-0.50} \left(\frac{t}{10^3 \text{ yr}}\right)^{1.254} \text{ pc},$$

where $\dot{E}_{38}$ is $\dot{E}$ in units of $10^{38}$ erg s$^{-1}$. In cases where $R_p$, $\dot{E}$, and $t$ are known, we can solve for $M_{ej}/E_{51}^{0.49}$; because $E_{51} \sim 1$ is expected, we have an estimate of the total ejecta mass. These quantities are known for 3C58 and G11.2–0.3 if the historical supernova identifications are assumed, and the results are given in Table 2. These estimates involve a spherical approximation for PWNe that are apparently not spherical, but an average radius can be taken (Woltjer et al., 1997; Roberts et al., 2002). The assumed distances are 3.2 kpc for 3C58 (Roberts et al., 1993) and 5 kpc for G11.2–0.3 (Green et al., 1988). The expected values of $M_{ej}$ for a core collapse supernova are typically several $M_\odot$ or more. In the case of a very fast Type Ic supernova, SN 1994I, $M_{ej}$ was only $\sim 1M_\odot$ (Iwamoto et al., 1994), which is an extreme case. The point is that the model leads to a value of $M_{ej}$ that is smaller than expected for 3C58. The radius is larger than would be expected if it were expanding into a normal supernova. There is no problem with G11.2–0.3.

### Table 2. Estimated ejecta and swept up mass

| Object     | $\dot{E}_{38}$ | Radio radius (pc) | $M_{ej}/E_{51}^{0.49}$ | Predicted $M_{sw} (M_\odot)$ | Observed $M_{sw} (M_\odot)$ |
|------------|----------------|------------------|-------------------------|------------------------------|------------------------------|
| 3C 58      | 0.27           | 3.3              | 0.1                     | 0.002                        | 0.1                          |
| G11.2–0.3  | 0.064          | 0.9              | 3.5                     | 0.05                         |                              |

Another constraint comes from the amount of mass swept up by the wind bubble, $M_{sw}$. An integration over the central density shows that $M_{sw} \approx 1.0 \dot{E} R_p^{-2} t^3$, fairly independent of supernova density distribution. Values of $M_{sw}$ deduced in this way for 3C58 and G11.2–0.3 are given in Table 2. The value of 0.002 $M_\odot$ deduced for 3C58 can be compared to the 0.1 $M_\odot$ found from X-ray observations (Bocchino et al., 2001). Again, there is a problem with the model mass being too low. The mass could be brought into agreement with the observed value if the age were increased by a factor $\sim 3$.

These models assume that the supernova ejecta are swept into a thin shell that remains spherically symmetric. However, the shell is being accelerated and is subjected to Rayleigh-Taylor instabilities, which can decrease the coupling between the pulsar wind bubble and the swept up gas. In the limit that there is no further acceleration after the ejecta are shocked, the PWN radius (eq. [2]) is increased by a factor of 1.4. The masses $M_{ej}$ and $M_{sw}$ are increased by a factor of 2, which does not change the conclusion about the difficulties with 3C58.

The model with constant $\dot{E}$ can be used to predict the internal energy in the PWN. This energy is reduced from the total deposited energy, $\dot{E}t$, because of work done on the surrounding supernova gas. For a range of flat central density distributions, the internal energy is $0.45 \dot{E} t$ (Table 1 of Chevalier and Fransson 1992). The internal energy in a PWN has relativistic particle and magnetic field components; a minimum value for the total energy in particles and fields can be found from the synchrotron luminosity and the emitting volume (e.g., Pacholczyk 1970; Tam et al., 2002).
discuss the radio emission from the PWN in G11.2–0.3. The value of the minimum energy deduced from the radio emission for the two PWNe is given in Table 3. The actual energy must be larger when a larger frequency range is considered. It can be seen that there is not a problem with the energy for G11.2–0.3, but that the energy in 3C 58 appears to be larger than that expected for the observed pulsar and the designated age. A larger age for 3C 58 would allow a larger energy to be deposited in the nebula.

| Object       | \(L_{\text{radio}}\) \((10^{34} \text{ ergs s}^{-1})\) | \(\dot{E}t\) \((10^{48} \text{ ergs})\) | \(E_{\text{min}}\) \((10^{48} \text{ ergs})\) | \(E_{\text{min}}/\dot{E}t\) |
|--------------|---------------------------------------------|-----------------|-----------------|-----------------|
| 3C 58       | 2.8                                        | 0.7             | 1.0             | 1.5             |
| G11.2–0.3   | 0.12                                       | 0.3             | 0.03            | 0.1             |

There are thus several arguments for 3C 58 being older than SN 1181, even though consider the identification to be secure. The problems are that the PWN is too large to be expanding into a normal supernova, the expected mass swept up by PWN smaller than observed, and the internal energy is larger than can be supplied by the pulsar. A larger age for the remnant is consistent with the slow expansion of 3C 58 observed at both radio (Bietenholz et al., 2001) and optical (Fesen et al., 1988) wavelengths.

**ENERGY EQUIPARTITION IN PWNe**

One of the important properties of a PWN is the relative amount of energy in particles and in magnetic fields. In the Crab Nebula, there is approximate equipartition overall in these energies. In the detailed MHD model of Kennel and Coroniti (1984) for the Crab Nebula, this property is produced by the choice of the \(\sigma\) parameter, the ratio of Poynting flux to particle kinetic energy flux in the pulsar wind. The value \(\sigma \approx 0.003\) is deduced; the magnetic field is relatively weak in the wind and is increased by the shock compression and further compression in the decelerating postshock flow. This value of \(\sigma\) is close to the upper limit that is allowed in this kind of model, or the flow would not be able to decelerate to meet the outer boundary condition, but there is no particular reason for this value to be produced.

One way to estimate the overall magnetic field in a PWN is from the synchrotron break frequency, \(\nu_{\text{br}}\), and the age of the PWN. The determination of \(\nu_{\text{br}}\) depends on the spectrum of the nebula. There is increasing evidence that the particle spectrum injected into PWNe typically has at least one intrinsic spectral break. Models for the radio to X-ray emission with a single power law injection spectrum generally fail (Reynolds and Chevalier, 1984), and the well-observed Crab Nebula spectrum requires an injection spectrum with a break (e.g., Amato et al., 2000). With synchrotron losses, the spectrum develops a further break.

Two PWNe for which there is age information and information on \(\nu_{\text{br}}\) are 3C 58 and MSH 15–52. As discussed above, 3C 58 may be older than 821 years, which I consider as a lower limit; a lower limit on the age yields an upper limit on the magnetic field. MSH 15–52 has been suggested to be the remnant of SN 185, although G315.4–2.3 is another candidate for the remnant of this supernova (Stephenson and Green, 2002). However, the large size of the nebula associated with MSH 15–52 (Gaensler et al., 2001) indicates that it is not significantly younger than 1700 years.

The determination of \(\nu_{\text{br}}\) depends on the interpretation of the overall spectrum of the PWN. For 3C 58 and MSH 15–52, as for most PWNe, there are detections at only radio and X-ray wavelengths. However, the fact that the extent of the X-ray emission is comparable to that of the radio emission in both cases indicates that \(\nu_{\text{br}}\) is not much lower than X-ray energies, assuming that particles originate close to the pulsar and move out in the nebula. In the case of 3C 58, the X-ray spectrum steepens at large radii, showing that synchrotron losses are significant in the X-ray regime (Torii et al., 2000). An estimate of \(h\nu_{\text{br}}\) is thus \(\sim 0.5\) keV, which is consistent with the fact that the X-ray spectrum is somewhat steeper than the spectrum from radio to X-ray wavelengths. The implications for the magnetic field and magnetic energy are given in Table 4. The magnetic field strength in MSH 15–52 can be estimated from similar arguments (Gaensler et al., 2001) and is given in Table 4. In this scenario, the low frequency breaks are intrinsic to the injected particle spectrum; this is a controversial point and there have been discussions of the low frequency breaks in
terms of synchrotron losses (e.g., Woltjer et al., 1997 on 3C 58 and Roberts et al., 2002 on G11.2–0.3).

Table 4. Comparison of magnetic and minimum internal energies

| Object     | $h\nu_{br}$ (keV) | $B$ ($\mu$G) | $E_B$ ($10^{47}$ ergs) | $E_{min}$ ($10^{47}$ ergs) |
|------------|-------------------|-------------|---------------------|-----------------|
| 3C 58      | 0.5               | 16          | 0.4                 | 10              |
| MSH 15–52  | 1                 | 8           | 0.3                 | 7               |

It is also possible to estimate minimum magnetic plus particle energy, $E_{min}$, from the radio synchrotron emission ($10^7 – 10^{13}$ Hz). The results, given in Table 4, show that the magnetic energy is considerably less than the total internal energy in both cases, so that the nebulae are particle dominated. In the context of the Kennel and Coroniti (1984) model, this would require a remarkably low Poynting energy flux in the pulsar wind. However, the result is consistent with the finding in the Kennel and Coroniti (1984) model that a particle dominated wind is needed to produce a shock front and deceleration of the flow to match the outer boundary. This suggests that pulsar winds may have a range of magnetizations, giving rise to a range of nebular properties. If cases with a highly magnetized wind occur, they would give rise to something other than a standard pulsar wind nebula. In this limit, the wind termination shock moves in to the pulsar [Rees and Gunn, 1974; Emmering and Chevalier, 1987], so that the immediate surroundings of the pulsar are in communication with the ambient medium.

DISCUSSION AND CONCLUSIONS

The increasing number of PWNe are providing many examples which can be compared to models initially developed for the Crab Nebula. In a model with interaction with freely expanding supernova ejecta, the PWN properties can provide a check on the age estimate for the nebula. Such models have previously been developed for the Crab Nebula, MSH 15-52, and 0540–69 [Chevalier and Fransson, 1992]. Recent observational results on 3C 58 and G11.2–0.3 allow similar models to be considered for these objects, which are of special interest because of their possible identifications with historical supernovae. The models indicate that 3C 58 is older than SN 1181, but that G11.2–0.3 is consistent with being the remnant of SN 386. These tentative conclusions need to be followed up by more detailed studies of the remnants. In both cases, the model predicts that the PWN is driving a shock front into freely expanding ejecta. Gas shocked in this way may have been observed in 3C 58 [Bocchino et al., 2001], but further observations are needed. Such gas has not yet been observed in G11.2–0.3. The external supernova remnant interaction also provides constraints on the system. This interaction is clearly seen in G11.2–0.3 [Roberts et al., 2002], but not in 3C 58, implying interaction with low density surroundings for that case.

Another finding here is that the 3C 58 and MSH 15-52 PWNe are particle dominated, which requires that the pulsar winds have a very low magnetization parameter. This property may be one of the reasons why these PWNe have low efficiencies of X-ray luminosity production compared to the pulsar power [Chevalier, 2000]. 3C 58, G292.0+1.8, G11.2–0.3, MSH 15-52, and G54.1+0.3 all have significantly lower levels of X-ray luminosity production efficiency than the Crab Nebula.

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