Discovery and Characterization of Superefficiency in Pulsar Wind Nebulae

Diego F. Torres\textsuperscript{1,2,3} and Tingting Lin\textsuperscript{1,3}

\textsuperscript{1} Institute of Space Sciences (ICE, CSIC), Campus UAB, Carrer de Magrans s/n, E-08193 Barcelona, Spain
\textsuperscript{2} Institutió Catalana de Recerca i Estudis Avançats (ICREA), Barcelona, Spain
\textsuperscript{3} Institut d’Estudis Espacials de Catalunya (IEEC), E-08034 Barcelona, Spain

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Abstract

We numerically study the radiative properties of the reverberation phase of pulsar wind nebulae. Reverberation brings a significant evolution in a short period of time. We show that even the Crab Nebula, associated with the more energetic pulsar of the sample that we consider, has a period in its future time evolution where the X-ray luminosity will exceed the spin-down power at the time. In fact, all of the nebulae in our sample are expected to have a period of radio, X-ray, and GeV superefficiency, and most will also have a period of TeV superefficiency. We analyze and characterize these superefficient phases.

\textit{Key words:} pulsars: general

1. Introduction

Recently, Younes et al. (2016) reported the discovery of a nebula surrounding the magnetar Swift J1834.9-0846. The fact that this system has the highest efficiency of all pulsar wind nebulae (PWNe) known was considered to be highly unusual: \( L_{\text{sd}} \sim 10^{34} \text{erg s}^{-1} \), is emitted just in soft X-rays. This promoted interpretations based on a transfer, via a yet-unknown mechanism, of magnetic energy into particle acceleration (Granot et al. 2017). However, we demonstrated that the multifrequency data, as well as its size, could be encompassed by a normal, rotationally powered PWN under the condition that it is entering into reverberation (Torres 2017). The latter is a relatively short but important phase in the evolution of all PWNe, produced when the reverse shock created by the supernova explosion travels back toward the pulsar, compressing the wind bubble (see, e.g., Slane 2017 for a review). This compression heats the PWN, reducing its size and increasing the magnetic field. Such evolution leads, as we see below, to an almost complete burn-off of the electron population. Despite the obvious importance of this phase, it is uncommon for radiative models of PWNe to consider it. In fact, the effect of reverberation upon the spectral results has been dealt with only in a few scattered occasions, and with different levels of detail; see, e.g., Gelfand et al. (2009), Vorster et al. (2013), Bandiera (2014), Bucciantini et al. (2011), Martín et al. (2016), and Torres (2017).

Here we study the radiative properties of the reverberation phase in detail. For this, we shall study the future reverberation period of well-characterized PWNe. We shall prove that the 10% efficiency found for Swift J1834.9-0846 is not a limit at any rate, not even for this pulsar, finding that all PWNe can have periods of superefficiency from radio to gamma-rays.

2. PWN Evolution

We use the code TIDE 2.3, which has been described in detail in Martín et al. (2016) and Torres (2017). Here we only add subroutines appropriate to compute efficiencies as a function of time, as described below. The main components and features of the model, apart that it takes into account the variation of the spin-down power, \( L_{\text{sd}} \), according to a given value of braking index, \( n \), are as follows.

1. The injection function for pairs is assumed as a broken power law, powered by the pulsar. The model computes the time evolution of the distribution subject to synchrotron, inverse Compton, and Bremsstrahlung interactions, adiabatic losses or heating, and accounting for escaping particles. Expressions for the radiative losses can be found in Martín et al. (2012).

2. The magnetic field of the nebula is also powered by the rotational power (the instantaneous injection is the fraction of spin-down that goes to power the magnetic field, \( \eta \)). The field varies in time as a result of the balance between this power and the adiabatic losses or gains of the field due to the expansion or contraction of the PWN (Torres et al. 2013).

3. The size of the PWN is computed according to age, progenitor explosion energy, medium density, velocity, and pressure of the supernova ejecta at the position of the PWN shell. We take into account that the latter profiles change if the PWN shell is surrounded by unshocked ejecta (thus the radius of the PWN is smaller than the radius of the reverse shock of the supernova remnant (SNR), \( R < R_{\text{rs}} \), or by shocked ejecta (where \( R_{\text{es}} < R < R_{\text{snr}} \), being \( R_{\text{snr}} \) the radius of the SNR). After reverberation, when the PWN pressure reaches that of the SNR, a Sedov expansion follows. Details are explicit in Section 3 of Martín et al. (2016).

The theoretical approach described is able to cope well with multifrequency data of known nebulae. The red curves in the top panels of Figure 1 shows the spectral energy distribution (SEDs) of the six PWNe (Crab, G09, G21, G54, Kes75, and J1834) that we take as examples in this work, at their corresponding age today as fixed or deduced from observations. The parameters for each model, together with the relevant pulsar’s observational data, are given in Table 1. Notation for all of the parameters follows that usually found in the literature, and is consistent with that used by us previously (Martín et al. 2016; Torres 2017). We divide parameters in Table 1 among measured or assumed, derived, and fitted values. Apart of these parameters we assume the following...
usual ones for all PWNe/SNR complexes: energy of the explosion $E_{SN} = 10^{51}$ erg, interstellar medium density $\rho_{ISM} = 0.5 \text{ cm}^{-3}$, SNR density index $= 9$, PWN adiabatic index $= 1.333$, and SNR adiabatic index $= 1.667$. We also consider the cosmic microwave background with $T_{cmb} = 2.73 \text{ K}$ and $\omega_{cmb} = 0.25 \text{ eV cm}^{-3}$). As expected, small variation in the fitted parameters are found when compared with similar models but that do not take into account reverberation (Torres et al. 2014).

Note that all PWNe studied are now relatively young and considered to be free-expanding, except for J1834. All other nebulae, including the Crab, will enter into reverberation sometime in their future. We choose these young nebulae (rather than other more mature ones) on purpose: as we shall see, reverberation is a very sensitive process, leading to a strong evolution where most of the electron population is wiped out. Because we are actually interested in the reverberation process itself, fixing the model parameters before

Figure 1. Spectral energy and electron distributions of the modeled PWNe along time. Each panel shows the evolution at different moments of interest for each nebula ($t_1 \ldots t_3$), which are introduced and discussed in the text, and includes also the results at the age today for comparison. The colored shadows in the electron panels note the Lorentz factor that have synchrotron-emitted characteristic energy in the X-ray band (0.1–10 keV) for the nebular magnetic field value at $t_1$ (black), $t_2$ (orange), and $t_3$ (blue), respectively. The shadows in the SEDs note the radio (1.4 GHz), X-rays (0.1–10 keV), GeV (0.1–10 GeV), and TeV (1–10 TeV) bands used to compute the corresponding luminosities.
this process happens makes more sense than doing it long after it ends.

Figure 1 shows the time evolution of the model fitting the current data for each of the PWNe considered. The two sets of panels show the electron and SEDs across time. A strong time evolution is expected. The times shown are chosen within and around the corresponding reverberation period of each PWN, and correspond to the times of the maximum PWN radius, $t_1 = \tau(R_{\text{max}})$, the maximum of the X-ray efficiency, $t_2 = \tau(\text{Eff}_x^{\text{max}})$, the minimum PWN radius, $t_3 = \tau(R_{\text{min}})$, and a later time already at the Sedov phase, $t_4 = \tau(\text{Sedov})$. Specific values for these times along the PWNe evolution of each nebula are also given in Table 1. The X-ray efficiency (and correspondingly, radio, GeV, and TeV efficiencies as well) are defined as the ratio of the luminosity emitted in a given frequency range at a given time with respect to the spin-down power at that same time, e.g., $\text{Eff}_x(t) = L_x(t)/L_{\text{sd}}(t)$. If at a time $t$ we measure this ratio to be larger than 1, we shall say that the PWN is superefficient.

3. Superefficiency

Figure 2 shows the time evolution of the calculated efficiencies in radio (1.4 GHz), X-rays (0.1–10 keV), GeV
(0.1–10 GeV), and TeV (1–10 TeV), together with the PWN radii. Table 1 shows the timescale for the duration of reverberation \((t(R_{\text{min}}) - t(R_{\text{max}}))\), the minimum radius, and the maximum magnetic field attained, as well as the properties of any super-efficiency period in radio, X-rays, GeV, or TeV energies (maximum efficiency, \(\text{Eff.}^{\text{max}}\); duration, \(\text{Dos}\); and the time at which the maximum efficiencies happen, \(t(\text{Eff.}^{\text{max}})\)). We also show the time \(t_4\) in the Sedov expansion used in the figures as an example of the spectra in this regime, and the values of the magnetic field at different times of interest.

Reverberation brings a significant evolution in a short period of time. Plotting efficiencies rather than distributions makes this evolution more clear.

The X-ray efficiency has several stages of increase and decrease that can be used to define different phenomenological phases. We call them phases a to c. We distinguish these phases via the following subsequent events: phase a has the PWN in free expansion, and lasts from the pulsar birth to the maximum of the nebula radius (at \(t_1\)). Phase b finishes at the maximum of the X-ray efficiency (at \(t_2\)). Phase c finishes at the minimum of the radius (at \(t_3\)). Phase d is the Sedov expansion, assumed to continue after \(t_3\). We use different background colors in Figure 2 to distinguish

Figure 2. Evolution of the PWNe efficiencies in X-rays (0.1–10 keV), GeV (0.1–10 GeV), TeV (1–10 TeV), and PWN radii along time. The second and fourth row provide zooms around the reverberation period, as shown in the corresponding global evolution panels.
these phases. Their spectral and electron properties at these times were shown in Figure 1. Note that in some cases, phase c is too short to be visible without a zoom in the reverberation period, as shown in the second and fourth rows of Figure 2.

Figure 2 shows that even the Crab Nebula, associated with the more energetic pulsar of the sample that we study, has a period in its future time evolution where, e.g., the X-ray luminosity will exceed the spin-down power at the time. In fact, all of the PWNe in our sample are expected to have a period of radio, X-ray, and GeV superefficiency, and all but Crab and J1834 will also have a period of TeV superefficiency. The finding of superefficiency at all frequencies dramatically shows how dangerous it is to rule out a pulsar of a given spin-down efficiency, and all but Crab and J1834 will also have a period of TeV superefficiency.

The zoomed panels in Figure 2 show that the moments at which the maximum efficiencies are attained are close but not exactly the same at different frequencies. This is a natural result of having electrons of different energies contributing to the photon spectrum at different frequencies. The number of electrons at a given energy is in turn a result of a balance between gains (via adiabatic heating) and losses (via radiation and escape) and the peak number is attained at different times for different energies. We also note that there is a variety of possibilities for which of these maximum efficiencies is the largest. Sometimes, like the case of J1834 and Kes 75, the largest maximum efficiency occurs for the X-rays. For more energetic pulsars like Crab, G09, or G21, it occurs at the GeV band. The evolution of the radio efficiency is quite similar for all PWNe. It shows a sharp peak happening close to the time of maximum of the compression. In this small timescale around \( t_3 \), all of the PWNe studied become superefficient in radio. However, the maximum efficiency attained in the radio band is typically smaller than that reached at higher frequencies; see Table 1.

The zoomed panels of Figure 2 can actually be considered as a proxy for the evolution of the luminosities themselves, in arbitrary units. In such a short period of time, the change of the spin-down power is small. In these zoomed panels, we note the appearance of a second peak in the X-ray efficiency for most of the cases studied (of which those appearing in Crab and G09 are examples). When such a second peak happens, it is closer to the time of the minimal radius. Whereas this second peak is only a local maximum, with the absolute largest X-ray efficiency happening at earlier times, it may also provide a second, and shorter, superefficiency period in some cases.

In the zoomed panels of Figure 2, we marked on some exemplary cases (Crab, G09, G54, and J1834) several times of interest between the times of the maximum of the X-ray efficiency and its second local maximum. At these times, we plotted the electron distribution, the synchrotron, and self-synchrotron Compton contribution to the photon spectrum, in Figure 3. This figure shows how the synchrotron-related processes dominate the shape of the spectrum at both low and high energies (compare Figure 3 with the corresponding total SED shown in Figure 1). This is particularly obvious when the two peaks in the SED appear clearly distinguished in energy at the time of maximum efficiency \( t_3 \).

We note that the maximum of the X-ray efficiency does not occur at the minimum of the radius, but at a time in between the start of reverberation and the minimum. This is in remarkable agreement with a result from analytical considerations of Bandiera (2014). This happens in all of the cases studied, and is a result of the energetic balance: a competence between electron heating by the nebular compression and how fast electrons escape or are cooled down via the emission of synchrotron radiation. The more compressed the nebula, the faster the electrons are cooled down (via synchrotron radiation in a larger magnetic field), and a smaller number of electrons are actually available to emit in X-rays. The competition between gains by adiabatic heating and losses by synchrotron along the critical time period is shown in Figure 4. They depict the timescales for energy gains and losses at the same times for which the corresponding SEDs and electron distributions were shown earlier. It can be seen that during most of the compression, synchrotron cooling has a shorter timescale than heating for the Lorentz factors of interest, and quickly burns off the electron population in all of the PWNe. This is consistent with the SEDs being dominated by synchrotron and self-synchrotron emission, and with the appearance of a second peak in the X-ray efficiency, as further discussed below.

Figures 3 and 4 also show the interval of Lorentz factors emitting synchrotron photons with characteristic energies \( (\nu_c = (3/4\pi) \gamma_e^2 (eB/mc)) \) between 0.1 and 10 keV (noted with black dots), and radio (1.4 GHz, noted with green dots). The Lorentz factors of interest for the emission of photons at these bands change significantly along the time evolution, even in this limited time extent, due to the strong variation in the magnetic field. This was also summarily shown in Figure 1, where we showed these intervals at \( t_2 = t(E_{\nu_c}^{\text{max}}) \) and \( t_3 = t(R_{\text{min}}) \). For these Lorentz factors of interest, and along the period shown, the number of electrons uniformly decreases, due to the cooling dominance.

At the beginning of phase c the peak of the synchrotron contribution to the SED, shown in the middle panel of Figure 3, is close to the X-ray band of interest, affecting the value of efficiency as a consequence of the band selection. If, instead, we were interested in the hard X-ray luminosity above 100 keV, the X-ray synchrotron flux would uniformly increase with time.

In addition to the X-ray luminosity variation via synchrotron, the X-ray flux is also affected by self-synchrotron emission (see the second and third panels of Figure 3). The latter radiation process dominates the production of the second peak. It happens at times when the Comptonized synchrotron spectrum actually peaks in X-rays instead of in gamma-rays. When it does, the flux in X-rays produced by self-synchrotron Compton emission may be one order of magnitude larger than that produced by synchrotron emission directly. This emphasizes how important it is to consider the self-synchrotron Compton process along the evolution of all nebulae, even when at later times it is usually completely irrelevant.

Note that when they happen, these second peaks occur closer to (but still before) the minimum of the radius. Note too that the GeV (and TeV) maximum efficiency always happens after the X-ray one. The reason for this is related to the fact that the self-synchrotron emission, which we compute following the formulae given in the Appendix of Martín et al. (2012), is quadratic in the number of electrons, inversely quadratic in the size of the nebula, and linear in the field. The electron influence is thus larger for self-synchrotron emission, given that they are also accounted for in the photon target distribution. However, the maximum efficiency moves toward later times when compared to the X-ray one, as the reduction of particles is
compensated for a longer time by the increase in the field and the decrease in the radius. With reverberation wiping electrons off quickly, once the maximum of the GeV luminosity is attained and starts to decrease there is no possible compensation for the loss of electrons. There is no second peak in GeV or TeV energy bands, because at these energy bands there is only one dominant process generating the SED, and the recovery can only happen when a sufficient number of high-energy electrons are rebuilt by the pulsar.

4. Concluding Remarks

Here we have shown that supereficiency periods in which the luminosity at a given band from radio to TeV exceeds the pulsar spin-down power are common. They are unavoidably associated with the reverberation process. Supereficiency happens because when the PWNe are reverberating, the spin-down power is no longer the energy reservoir. In these cases, the nebulae are receiving energy from the environment, and the spin-down power is a priori not determinant to judge detectability at any band.

Observing one such supereficient system, a bright, small, or point-like nebula with a spatially coincident pulsar many times less energetic, would be amazing. The difficulty in observing them is that such systems can be maintained for only a few hundred years. For the estimate that follows, let us assume that the supereficiency period roughly lasts around 300 years in the evolution of young nebulae, typically <10,000 years of

Figure 3. Details of the time evolution of the electron distribution and the synchrotron and self-synchrotron Compton contribution to the photon spectrum around the time of minimum radii and maximum efficiency, between $t_2$ and $t_3$ in the corresponding panels of Figure 1. Times are color-coded as described in the left panels.
age (although note that as the G54 case tells, supernova with large ejected masses or low-density environments can produce reverberation beyond this age). Assuming a pulsar birthrate of $3 \text{ century}^{-1}$ (Faucher-Giguère & Kaspi 2006), 300 PWNe were born within the last 10,000 years; from these, we are interested in a period equivalent to—at most—3% of their evolution. Taking into account the correspondingly shorter percentages for pulsars born at different centuries, we have a probability of ∼1% of finding one of these pulsars in the right period of their evolution. Thus we expect at most three PWNe in a superefficient stage in the Galaxy today. This should be taken as an upper limit, because it assumes that it is equally probable to have reverberation at any time within the first 10,000 years of a pulsar (thus neglecting the fact that there is no reverberation in their free-expansion phases). In a future work, we will focus on observational strategies for finding super-efficient or highly efficient PWNe.

Note that our model assumes no morphological shape for the PWN; they are described with a time-varying radius. If the compression is asymmetric or if turbulence develops, super-efficiency could be less effective, thereby detaining the reduction in the PWN size and the increment in the field. In particular, this might affect less-energetic nebulae such as Kes 75 or J1834, and will likely be unimportant for others such as G09, G21, or Crab. Magnetohydrodynamical simulations will verify this issue. In any case, $R_{\text{min}}$ is many orders of magnitude larger than the pulsar’s radius, or even the pulsar’s magnetosphere (typically at least 6 orders of magnitude larger than the size of a young pulsar’s light cylinder), and thus the inner workings of the pulsed emission via synchro-curvature radiation (e.g., Torres 2018) is not expected to be significantly affected, even in the most severe of the compressions.

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ORCID IDs

Diego F. Torres © https://orcid.org/0000-0002-1522-9065

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