THE “SWAN SONG” OF THE PULSAR WIND NEBULAE

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ABSTRACT:

Bamba et al. (2010) used deep X-ray observations to estimate sizes of faint and old Pulsar Wind Nebulae (PWNe). They found a steady increase in size with the nebular age, up to ages of ~10^5 yr. Their conclusion was that these PWNe keep expanding up to large ages, contrary to the expectation that a reverse shock from the associated supernova remnant (SNR) squeezes the PWN before the beginning of the Sedov phase. In order to allow X-ray emitting electrons to reach large distances from the pulsar without being burnt by synchrotron losses, Bamba et al. assumed that the nebular field is very weak and/or that these electrons are diffusing out efficiently.

Here I propose a different scenario, where the observed trend arises from the combination of objects expanding under a wide range of ambient densities. PWNe re-brighten considerably near the time at which they are compressed by the reverse shock, and this represents for many of them the last chance to become detectable. The time at which this phase takes place also depends on the ambient medium density. By assuming reasonable values for the supernova and pulsar initial conditions, the observed trend is naturally reproduced.

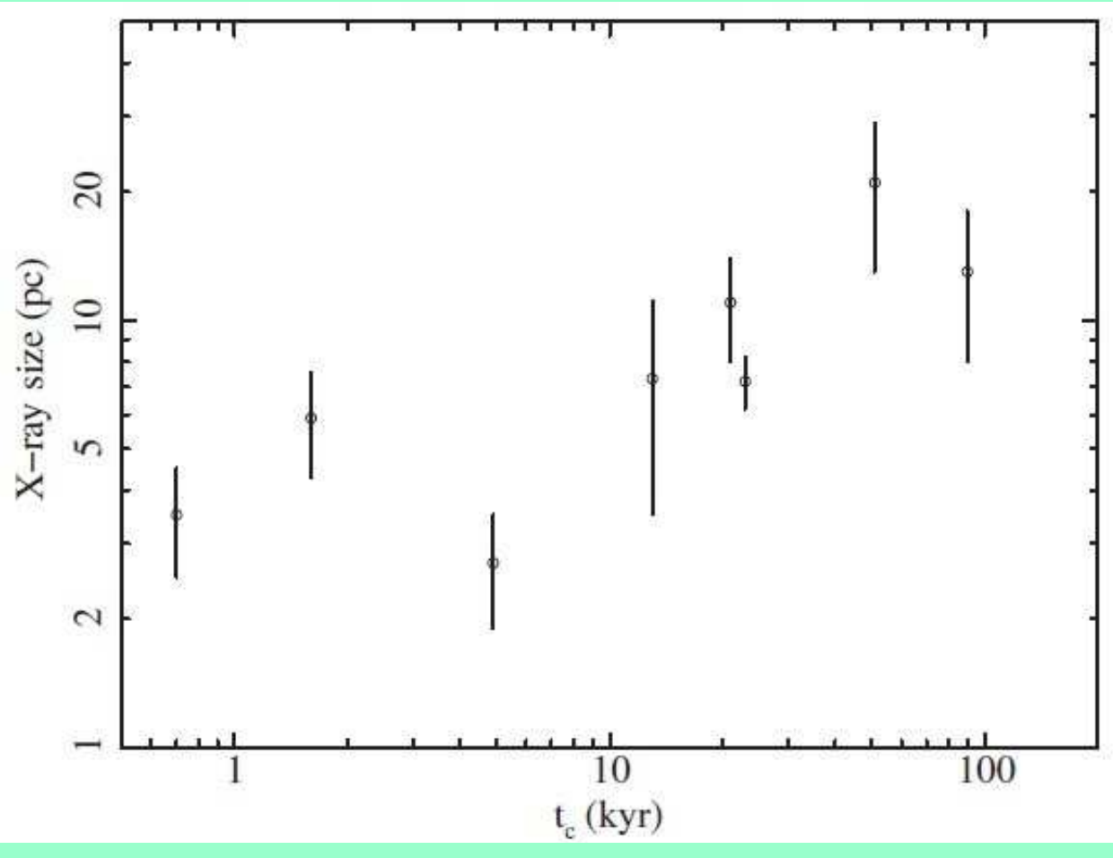
Also the correlation found by Mattana et al. (2009), between the X-ray PWN flux and the pulsar spin-down luminosity, can be explained by the same scenario. In these old objects, before the PWN compression phase the nebular magnetic field is very low, then X-ray electrons suffer negligible synchrotron losses and can build up a flatter energy distribution. This may justify the correlation, discovered by Gotthelf (2003) and confirmed by Li et al. (2008), between he X-ray photon index and the PWN age.

THE HUGE SIZES OF OLD PULSAR WIND NEBULAE

With the H.E.S.S.-discovered γ-ray nebulae and their X-ray counterparts, the sample of non-thermal nebulae associated to pulsars has considerably increased, including also older systems (up to ~10^5 yr). This has further stimulated investigations of how aged PWNe should look like at high energies.

Kargaltsev & Pavlov (2010) concluded that *“TeV PWNe sizes generally increase with pulsar age while the X-ray PWN sizes show an opposite trend”*.

On the other hand, Bamba et al. (2010) found that *“A systematic study of eight of these PWNe ... has revealed that the nebulae keep expanding* [also in the X-rays] *up to 100 kyr”* (ages are estimated using the pulsar characteristic spin-dowm time).



The latter study ends posing some questions:

1. Why the inferred PWN size evolution does not show any sign of contraction, as expected instead at the arrival of the SNR reverse shock?
2. How the X-ray emitting electrons may travel so far from the pulsar, without being burnt by synchrotron losses?

SYNCHROTRON LOSSES TIME SCALE: $2\left(\frac{B}{10\,\mu\mathrm{G}}\right)^{-3/2}\left(\frac{\epsilon_{\rm syn}}{1\,\mathrm{keV}}\right)^{-1/2}$ kyr,

Bamba et al. conclusions are:

1. The nebular field must decrease with time down to very low values.
2. Electrons must efficiently diffuse out from the PWN.

(and, anyway, it is not explained how such large sizes can be reached)

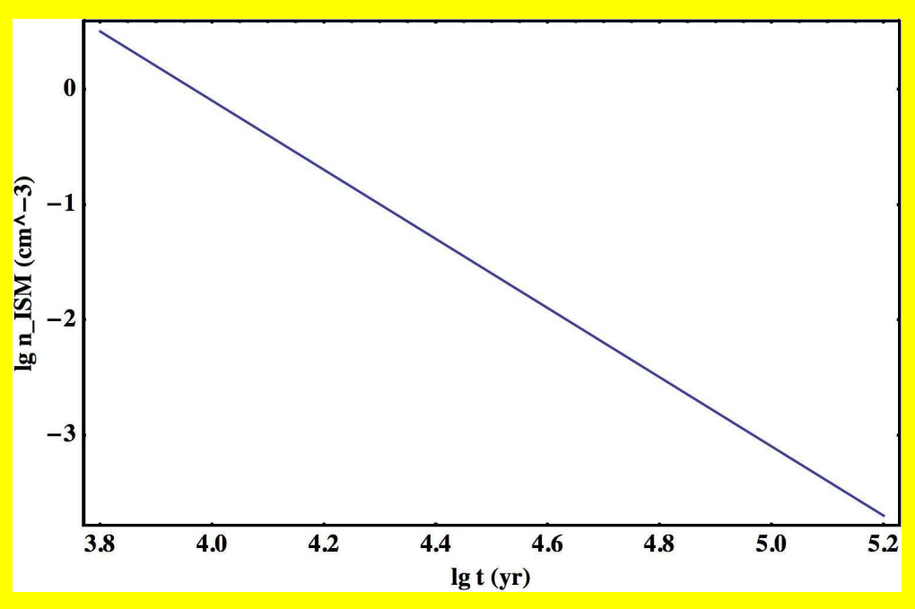
I will show that we do not really need these two “ad hoc” assumptions.

BAMBA ET AL. RELATION AS A COMBINED EFFECT

1. The observed “time evolution” of the PWN radius may not reflect the actual evolution of an “average” PWN. It could be, instead, the combined effect of objects evolving under a wide range of conditions.

THE MOST RELEVANT DIMENSIONAL PARAMETERS: $E_{\rm SN},\quad M_{\rm SN},\quad \dot{E}_\circ,\quad \tau_\circ,\quad \rho_{\rm ISM}$

2. PWNe present in the sample are those that were most easily detectable. In the case of older PWNe, a special time at which the PWN re-brightens is close to arrival time (t_c) of the SNR reverse shock. Because of compression, the nebular field increases, then increasing the effectiveness of synchrotron emission.

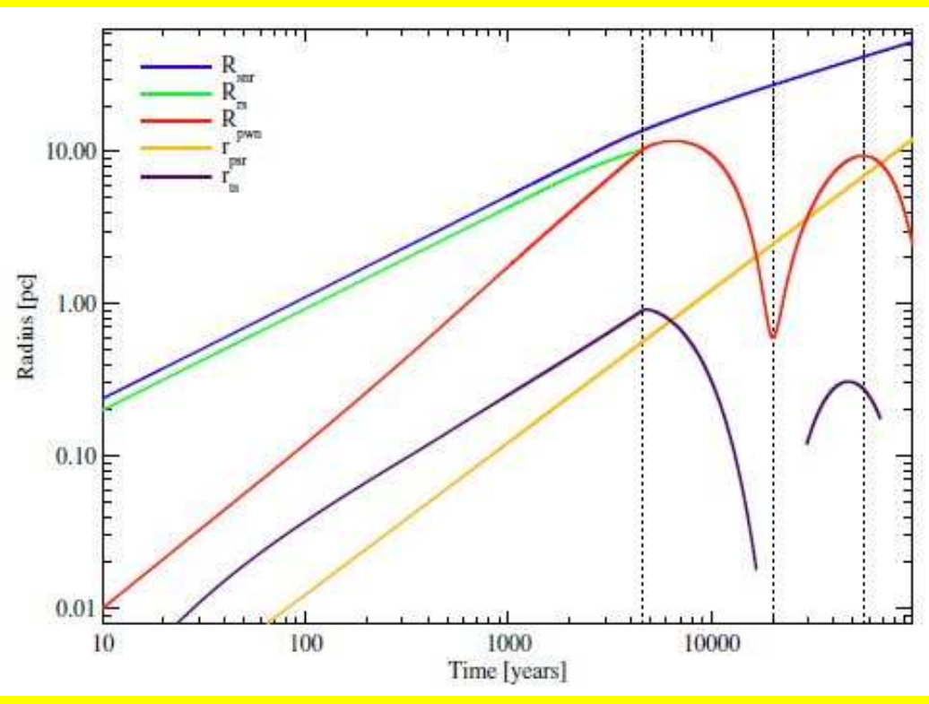


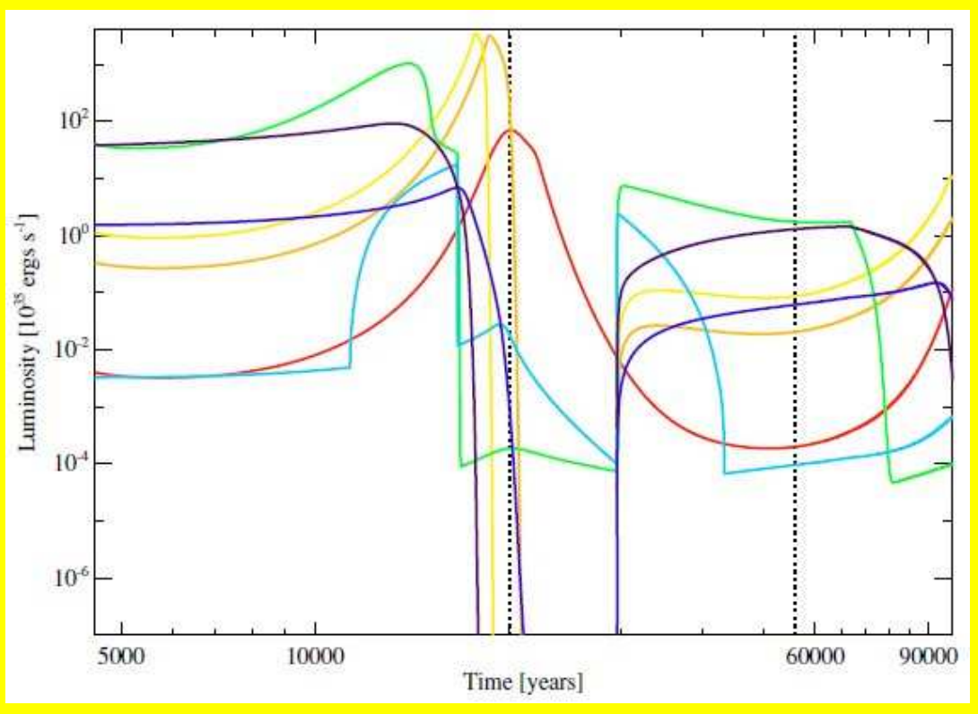
This time not only depends on the SN parameters, but also on the ambient density, which may largely vary from case to case. Indeed, the ages of PWNe in the Bamba et al. sample correspond to quite reasonable values for the ISM density (10^{-3}—1 cm^{-3}).

$$t_c \sim \frac{M_{\rm SN}^{5/6}}{\rho_{\rm ISM}^{1/3}E_{\rm SN}^{1/2}}$$

$$E_{\rm SN} = 10^{51}\,\mathrm{erg};\quad M_{\rm SN} = 8M_\odot;\quad n_{\rm ISM} = 0.1\,\mathrm{cm}^{-3};$$
$$\dot{E}_\circ = 10^{40}\,\mathrm{erg\,s^{-1}};\quad \tau_\circ = 500\,\mathrm{yr};$$
$$\eta_e = 0.999;\quad \eta_B = 0.001;\quad \eta_P = 1$$

The analysis presented here is essentialy a dimensional one. For details and numerical scalings I refer to the numerical model by Gelfand et al. (2009), which corresponds to t_c =20,000 yr, and whose parameters are reported in the table. The red line in the left figure shows the evolution of the PWN size. The right figure shows the evolution of the emission in several spectral ranges: at lower photon energies (radio=red; mid-IR=orange; optical=yellow) a strong emission peak appears near the squeezing time; while at higher energies (soft X-rays= green), the peak occurs slightly earlier, when the synchrotron time becomes comparable with the compression time. In the following I will present results under the simplifying assumption that the emission peaks around t_c.





At times later than $\tau_\circ$ (the pulsar spin-down time at birth) the magnetic flux built up during the earlier phase is approximately conserved:

$$\Phi_B(\tau_\circ) \sim B_{\rm PWN}R_{\rm PWN}^2 \sim \frac{\eta_P^{1/10}\eta_B^{1/2}\dot{E}_\circ^{3/5}\tau_\circ^{11/10}E_{\rm SN}^{3/20}}{M_{\rm SN}^{1/4}}$$

After the reverse shock has reached the PWN, its magnetic pressure is roughly balancing the SNR pressure (given by the Sedov solution). Putting all pieces together, one finally gets this relation for the PWN size:

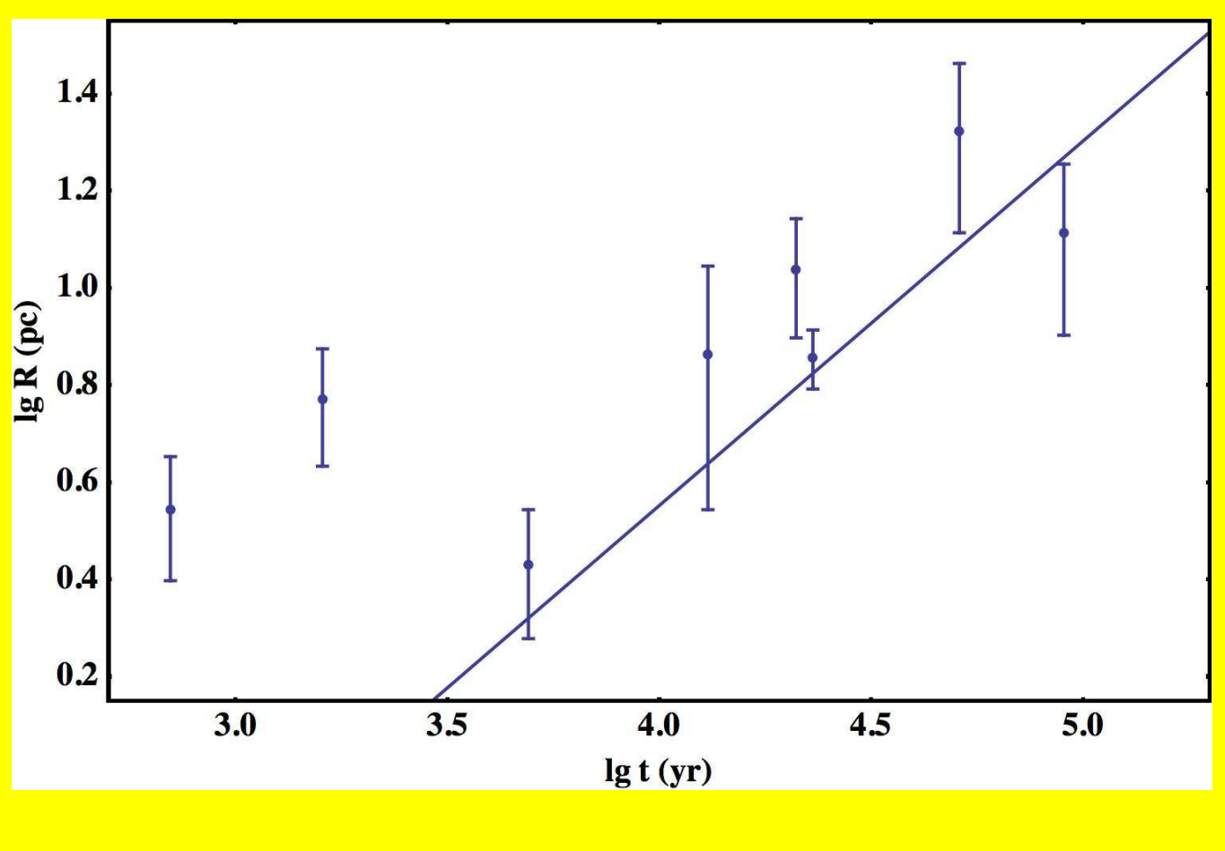
(tilded quantities are scaled with Gelfand et al. model)

$$R_{\rm PWN} = 3.6\left(\frac{\tilde{\eta}_P\tilde{\eta}_B^5\tilde{\dot{E}}_\circ^{6}\tilde{\tau}_\circ^{11}\tilde{E}_{\rm SN}^4}{\tilde{M}_{\rm SN}^{10}}\right)^{1/20}\left(\frac{t}{10,000\,\mathrm{yr}}\right)^{3/4}\ \mathrm{pc}$$

This formula is plotted against Bamba et al. observations: the agreement is quite good, especially considering that IT IS NOT A FIT, but simply uses the pulsar and SN parameters as taken by Gelfand et al.

The two first points in the figure (Kes 75 & MSH 15-52) were not expected to follow the trend, simply because they are young PWNe, which have not been reached as yet by the reverse shock.

Finally, this relation holds ONLY for PWNe that are still embedded in their SNRs; in particular it is not valid for pulsar bow-shock nebulae.



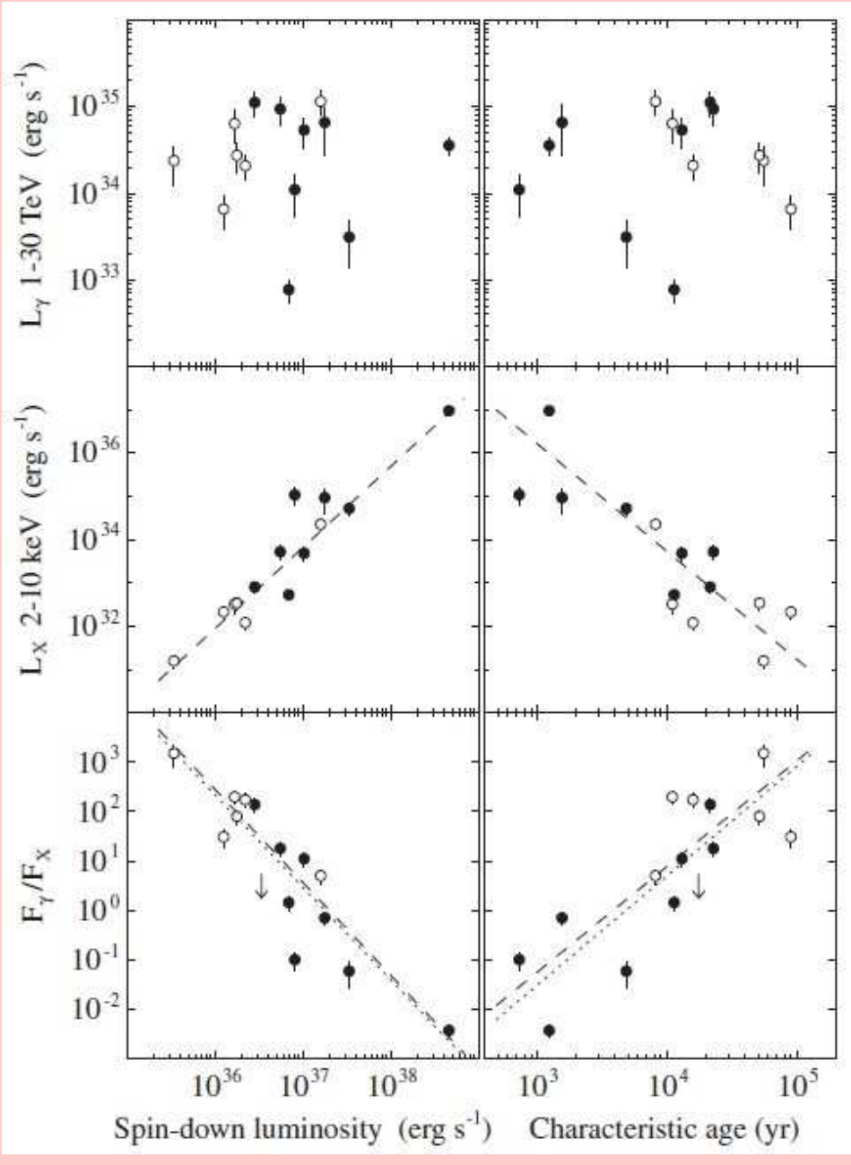
HIGH-ENERGY EMISSION OF AGED PWNE

Mattana et al. (2009), studying a sample of PWN detected both in the X-ray and TeV renge, pointed out a very tight correlation between L_X and the pulsar Edot (or alternatively the pulsar characteristic age). A weighted least-square fit gives:

$$\log_{10} L_X = (33.8 \pm 0.04) + (1.87 \pm 0.04)\log_{10}\dot{E}_{37}.$$

Instead, the TeV emission (L_γ) does not show any clear correlation.

The explanation proposed by Mattana et al. is that *“the X-ray emission traces the recent history of the nebula, whereas the γ-ray emission traces a longer history, possibly up to the pulsar birth”*.



MODELLING THE X-RAY EMISSION

Consistently with the scenario presented here, one could predict the “evolution” in X-rays (again with the same meaning as for the “size evolution”, namely that it is a combined effect, completely unrelated to the actual time evolutions of the individual objects).

Main features of the model are the following:

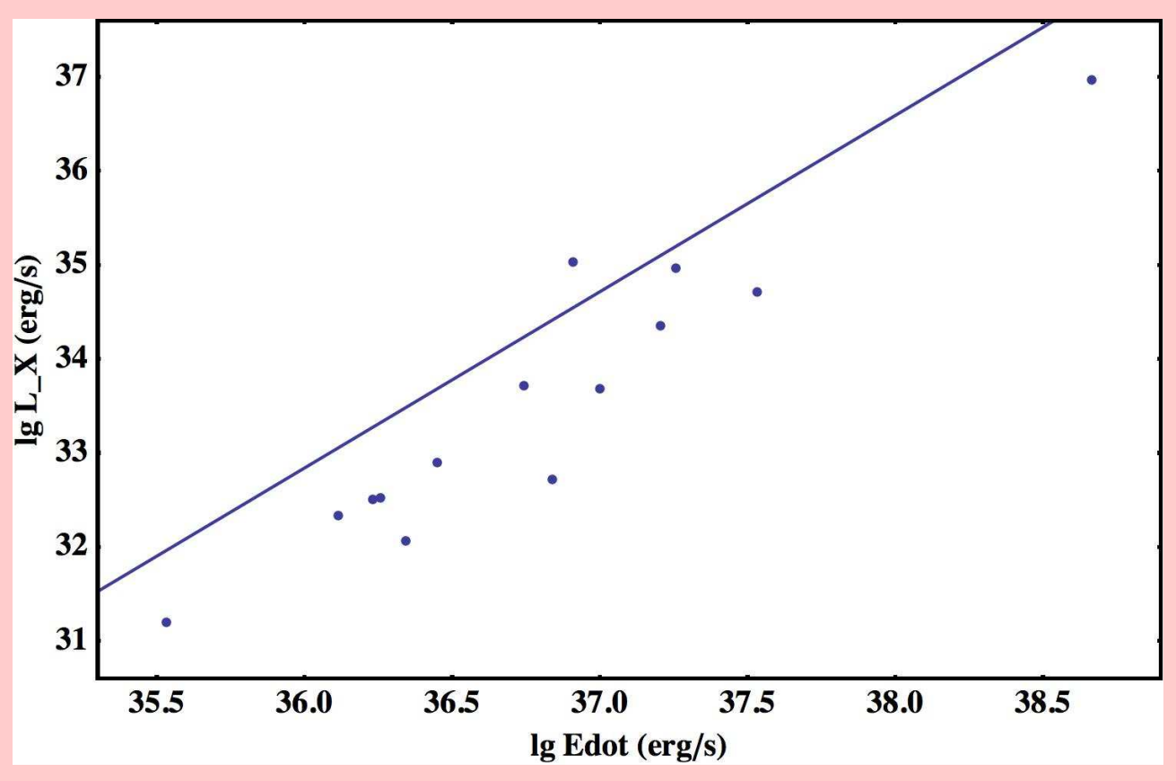
1. It assumes a “universal” power-law distribution of the injected electrons (with power-law index $\alpha\cong2$).
2. When PWNe are young, synchrotron losses dominate the evolution of X-ray emitting electrons.
3. But later on, with the expansion magnetic fields become so low (of order of microG) that even X-ray emitting electrons evolve adiabatically.
4. At the arrival of the reverse shock, and subsequent PWN crushing, these electrons eventually burn out by synchrotron losses.
5. The relevant phase for the maximal emission is when synchrotron losses and compression gains roughly balance.

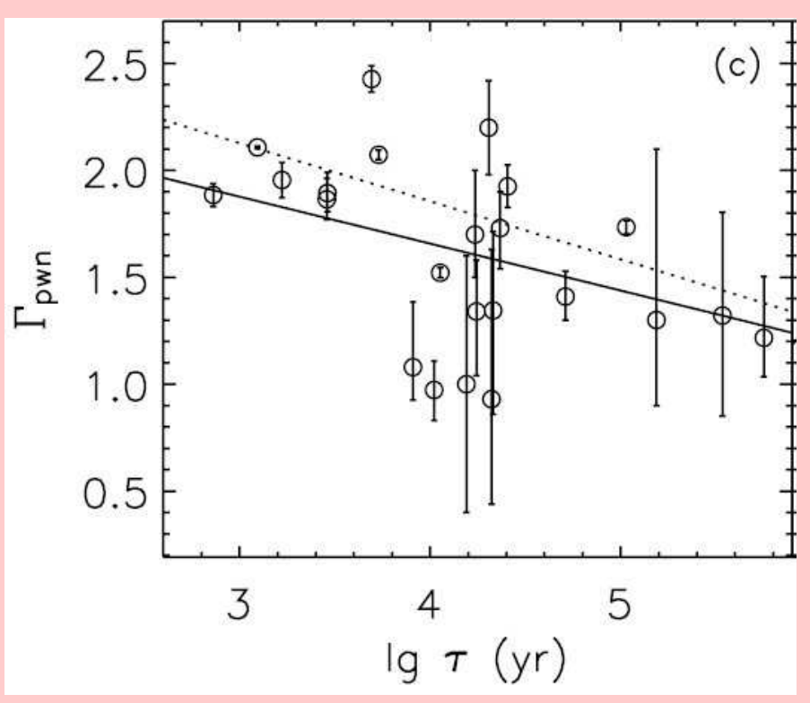
Assuming that the PWN size at that time scales with the PWN size at the maximum squeezing, a self-similar treatment can be applied, leading to the following formula:

$$L_X(\dot{E}) \simeq \frac{10^{36}\,\mathrm{erg\,s^{-1}}}{\ln(\gamma_{\max}/\gamma_{\min})}\left(\frac{\tilde{\eta}_e^{40}\tilde{\eta}_B^{20}\tilde{M}_{\rm SN}^{45}}{\tilde{\eta}_P^{12}\tilde{\dot{E}}_\circ^{27}\tilde{\tau}_\circ^{42}\tilde{E}_{\rm SN}^{23}}\right)^{1/40}\left(\frac{\dot{E}}{10^{37}\,\mathrm{erg\,s^{-1}}}\right)^{15/8}$$

Taking $\ln(\gamma_{\max}/\gamma_{\min})$ = 20 and using again the model parameters as from Gelfand et al., the expected trend matches rather nicely the data (again, THIS IS NOT a FIT), and especially well the slope of the correlation (15 / 8 = 1.875 against the observed 1.87 from Mattana et al.).

[Note: the 3 X-ray brightest PWNe in the plot, namely Crab, Kes 75, and MSH 15-52 are not described by the above scenario]





While young PWNe have typically X-ray spectral indices ~1 (i.e. photon indices ~2), crushed PWNe are expected to show harder X-spectral indices (~0.5), even if the spectral index at injection is constant. This because now the electron distribution is built up in the adiabatic regime. Indeed, there is observational evidence for typically harder X-ray spectra in older PWNe (Gotthelf 2003; Li et al 2008, from which the figure to the left).

ABOUT THE TEV EMISSION

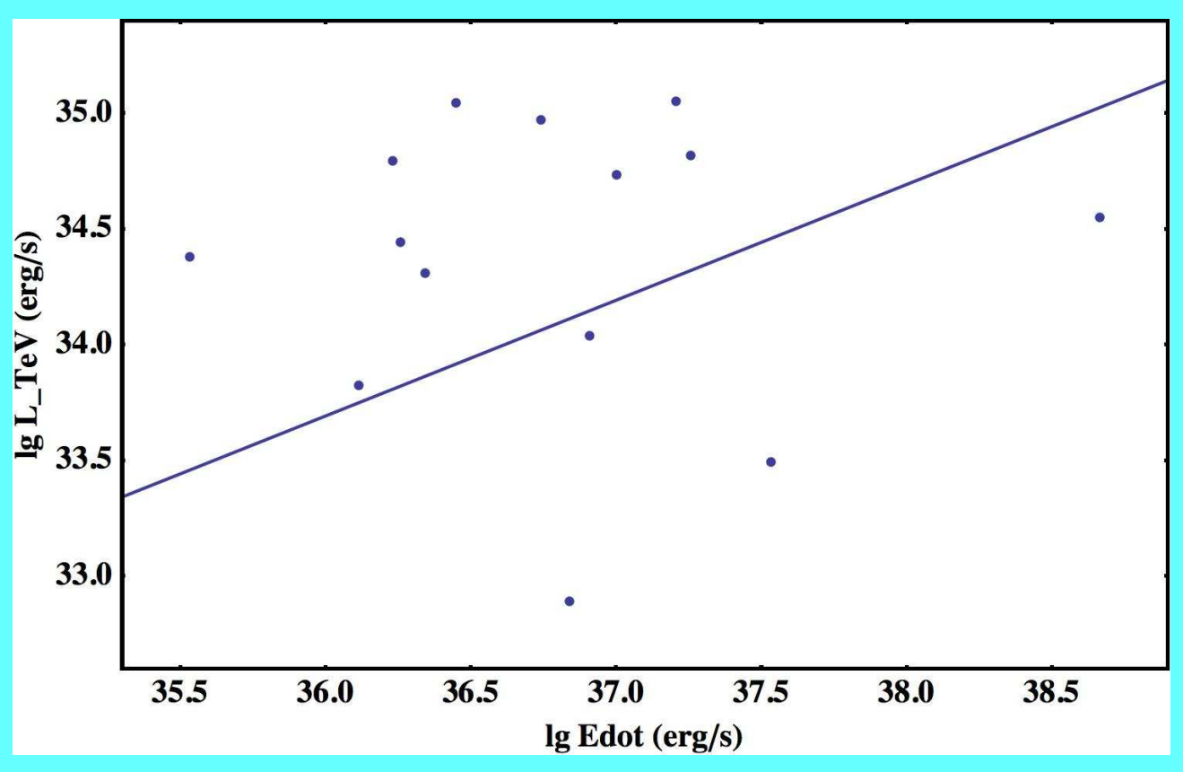
I assume that the observed TeV emission originates from Inverse Compton (IC) scatterings on the same electrons that produce the synchrotron spectrum. Incidentally, within the above scenario, hadronic emission is unlikely to dominate just because of the lack of targets (we have seen that low ISM densities are expected for most old PWNe).

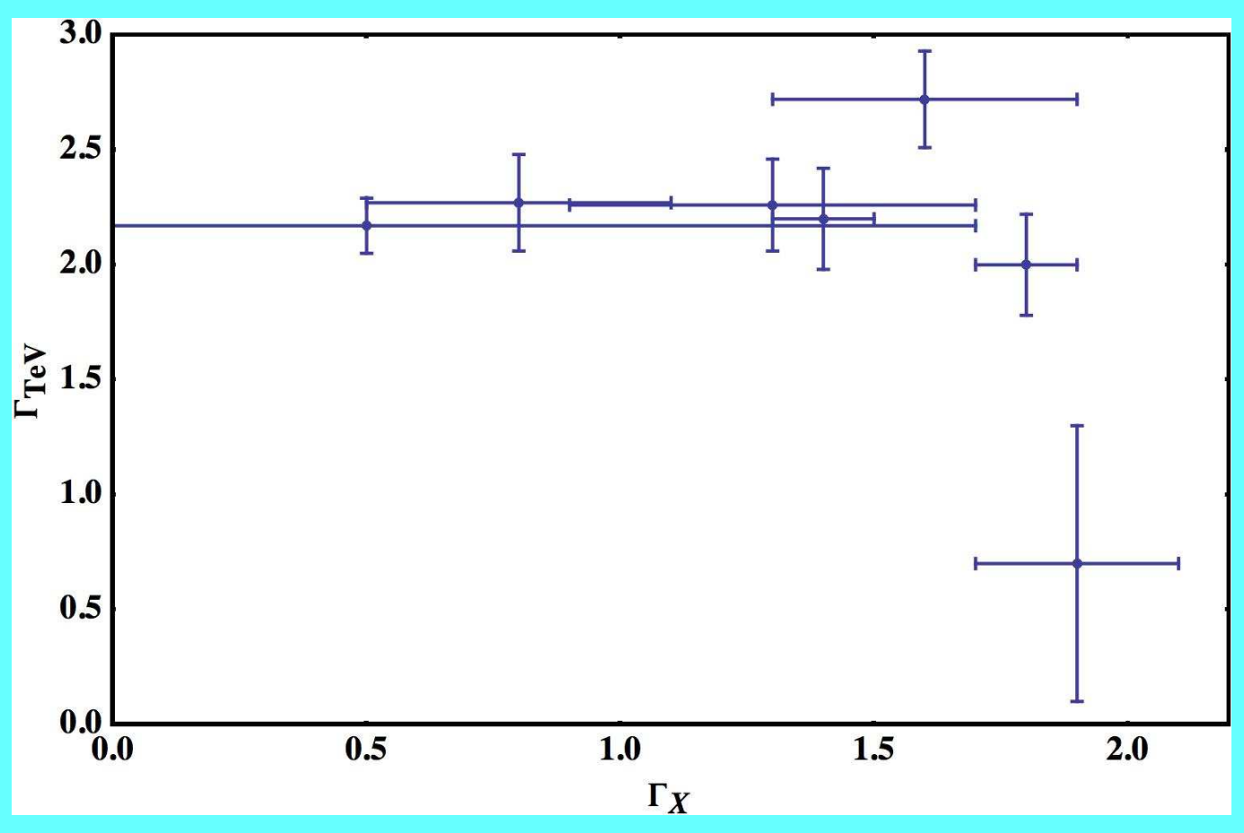
In the case of IC scattering against the CMB photons, TeV emission can be estimated as:

$$L_{\rm TeV}(\dot{E}) \simeq \frac{3\times10^{35}\,\mathrm{erg\,s^{-1}}}{\ln(\gamma_{\max}/\gamma_{\min})}\tilde{\eta}_e\tilde{\dot{E}}_\circ^{1/2}\tilde{\tau}_\circ\left(\frac{\dot{E}}{10^{37}\,\mathrm{erg\,s^{-1}}}\right)^{1/2}$$

For pulsar+SN conditions like in Gelfand et al. model, the associated TeV emission can be evaluated.
It should have a slight dependence on the pulsar spin-down power. It is possible that this dependence is washed out in the data by the dispersion in source parameters, even though in this case it is not easy to understand why the L_X-Edot correlation shows small dispersions.

By comparing the predictions with the actual detections (from Mattana et al. See figure to the right), we can also notice that the predicted values are tipically lower than the actual ones. This suggests the presence of a further component of scattered photons, beyond the CMB ones.





In addition, the TeV spectrum is generally softer than the X-ray one. This would imply that IC scatterings are in the Klein-Nishina regime, then requiring photons with higher temperatures than the CMB ones.

All this is in agreement with the finding of Bucciantini et al. 2011, which in order to fit the synchrotron + IC spectra of some (although younger) PWNe, need to introduce a further diluted black-body component of photons, with T=400-1000 K.

CONCLUSIONS:

- A scenario is proposed, valid for older PWNe that are still embedded in their SNRs. It is shown that the PWN re-brightening phase following its compression by the SNR reverse shock represents a good chance, and possibly the last one, for an old PWN to become detectable.
- The observed correlations of the PWN size and X-ray luminosity with the PWN age do not represent a “typical” evolutionary path, but are more naturally explained as the combined effects of PWNe evolving under very different ambient density conditions.
- Both luminosity and spectral slope of aged PWNe in the TeV range indicate that the γ-ray emission cannot be explained by IC scattering of CMB photons only, but require the presence of a further, warmer component of photons.