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Middle aged PWNe: Hints on the reverberation process

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THE PROBLEM

A pulsar wind nebula (PWN), in the early phases of its evolution, is confined by the freely expanding supernova (SN) ejecta, and its main dynamical effect is that of carving a cavity by pushing away the innermost layers of these ejecta. During this phase the PWN expansion is mildly accelerated, as long as the pulsar is releasing most of its spin energy, and then approaches a linear expansion. At a later phase of the evolution of the surrounding SNR, a reverse shock (RS) proceeds towards the center, and eventually enters into contact with the matter swept up by the PWN and with the PWN boundary itself. The associated extra pressure stops the PWN expansion and reverts it into a contraction, whose extent depends on how powerful the PWN is. This phase is called "reverberation".

IMPORTANCE OF THE REVERBERATION PHASE

The main effect of reverberation is to "rejuvenate" PWNe that otherwise would be too old and weak to be investigated, or to be detectable at all. The compression enhances the magnetic field strengths, and adiabatically powers the relativistic particles. As a result, the synchrotron emissivity may increase considerably, as well as the inverse Compton (IC) one. The effects of this phase can be mainly observed at X-ray energies (synchrotron) and in the TeV range (IC), and could be of paramount importance to investigate the late evolution phases of a large population of PWNe, with implications also on the stellar evolution.

OUR GOALS AND APPROACH

GOALS

- to model reverberation under the widest possible range of conditions
- to investigate the dependence on the parameters

COMPLEXITY

- large number of models to be investigated
- single model complexity: asymmetry of the PWN; anisotropies in the surrounding material (SNR, ISM); ambient density gradients; small-scale turbulence; structure of the magnetic field; radiation losses;
- realistic modeling requires a full 3D approach → unrealistically huge computational times/resources.

APPROACH

Solve the complexity by using 1D hydrodynamic (HD) numerical models (with the PLUTO code, Mignone et al. 2007), in spherical symmetry, neglecting the dynamical effects of radiative losses. Results should be compared with Torres & Lin 2018 [TL18], where a more simplified dynamical model is used, but the effects of radiative losses on the dynamics are included (with the TIDE code, Martín et al. 2016).

METHOD

Limitation of the number of parameters

In principle the number of parameters affecting the evolution of a PWN is large:

1. Initial pulsar parameters: luminosity (L_0), spin-down time (τ_0), braking index (n_{sd});
2. Supernova parameters: released energy (E_{sn}), mass of the ejecta (M_{ej})
3. Density of the ISM (ρ_{ISM})

We note however that scaling laws can be applied, using characteristic dimensional units scaled with E_{sn}, M_{ej}, and ρ_{ISM} (in a similar way as presented in Truelove & McKee 1999):

→ spatial dimension: $R_{\rm ch} = M_{\rm ej}^{1/3}\rho_{\rm ISM}^{-1/3}$

→ time: $t_{\rm ch} = E_{\rm sn}^{-1/2}M_{\rm ej}^{5/6}\rho_{\rm ISM}^{-1/3}$

→ luminosity: $L_{\rm ch} = E_{\rm sn}^{3/2}M_{\rm ej}^{-5/6}\rho_{\rm ISM}^{1/3}$

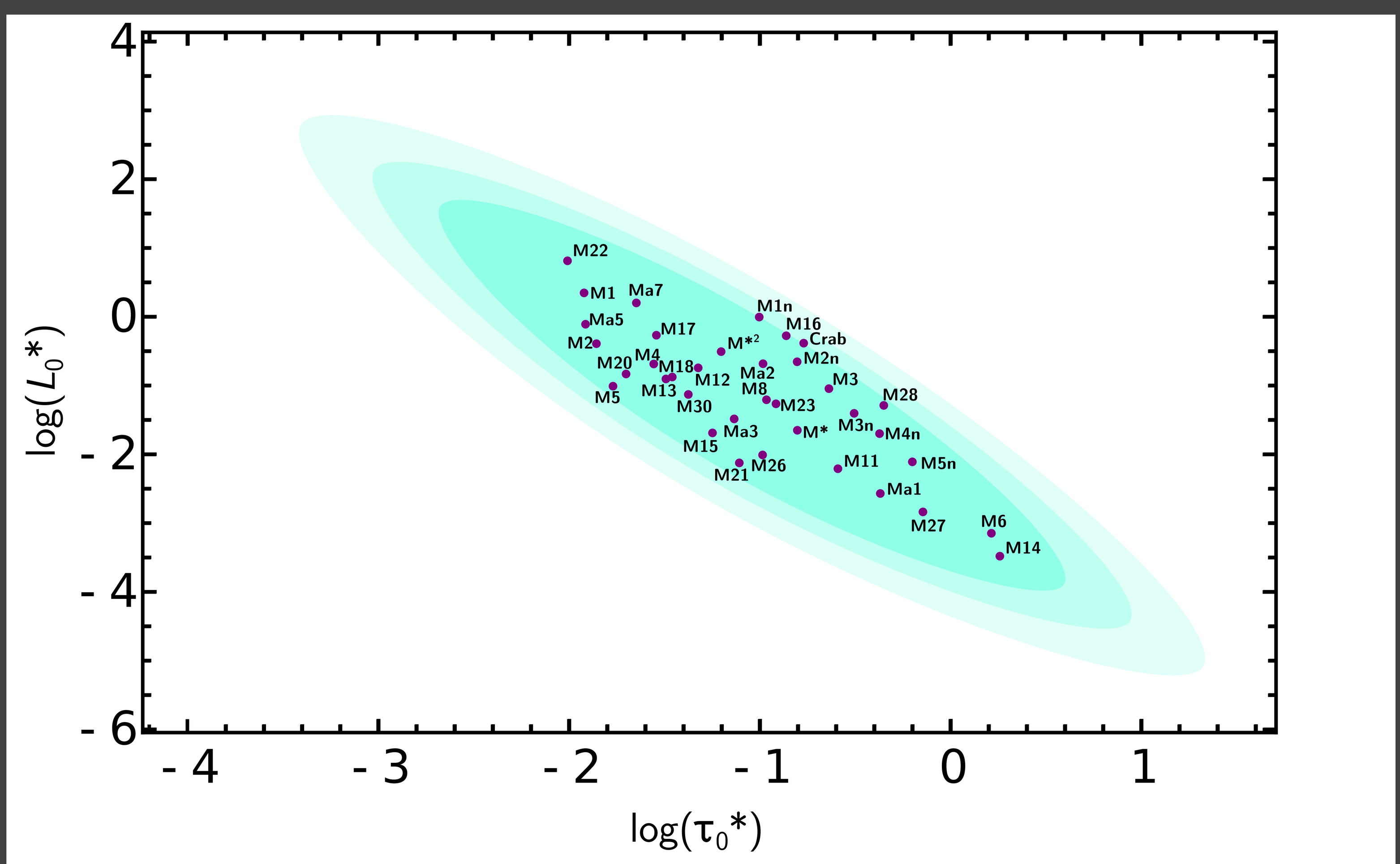
In this way the model parameters can be reduced to the two dimensionless ones:

$$L_0^* = L_0/L_{\rm ch} \qquad \tau_0^* = \tau_0/t_{\rm ch}$$

Other dimensionless parameters, related to the shape of the ejecta profiles and to the pulsar spin-down law have been fixed to rather usual values (flat ejecta, n_{sd}=2.33).

THE MODELS

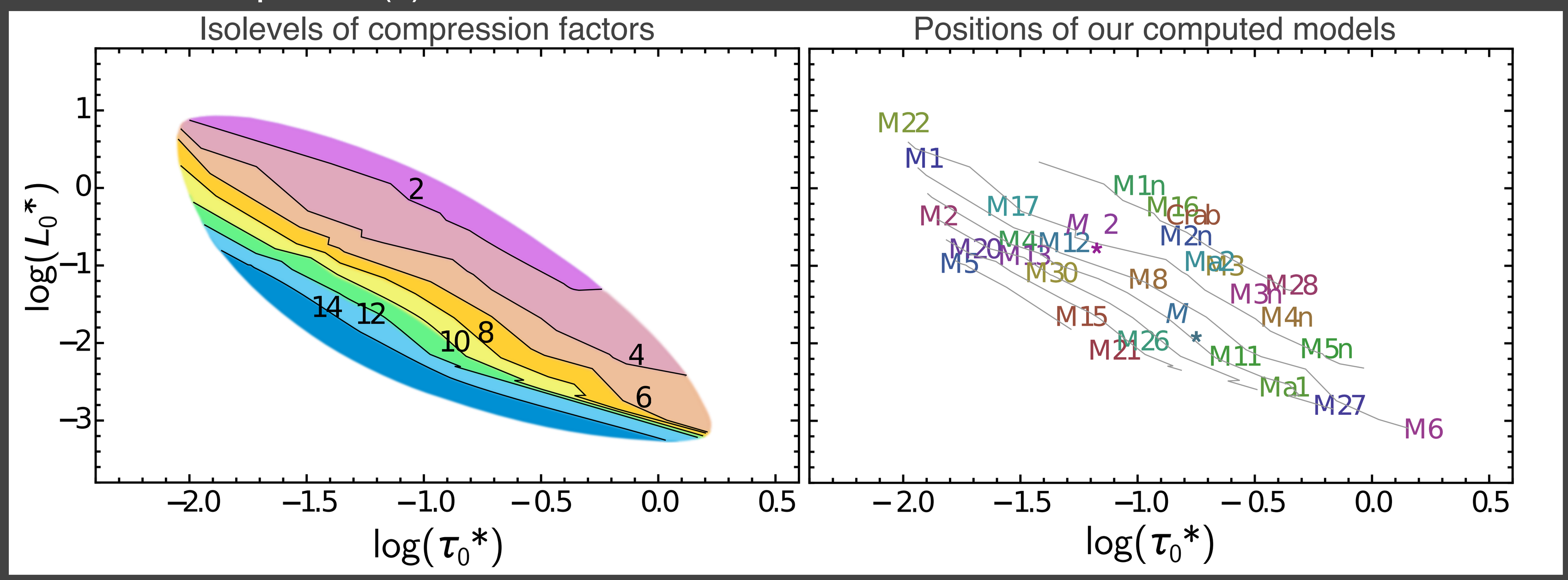
We consider a large number of models covering a wide part of the pulsar-populated region (in light blue shades, as deduced from Faucher-Giguère & Kaspi 2006) in the (L_0*,τ_0*) plane.



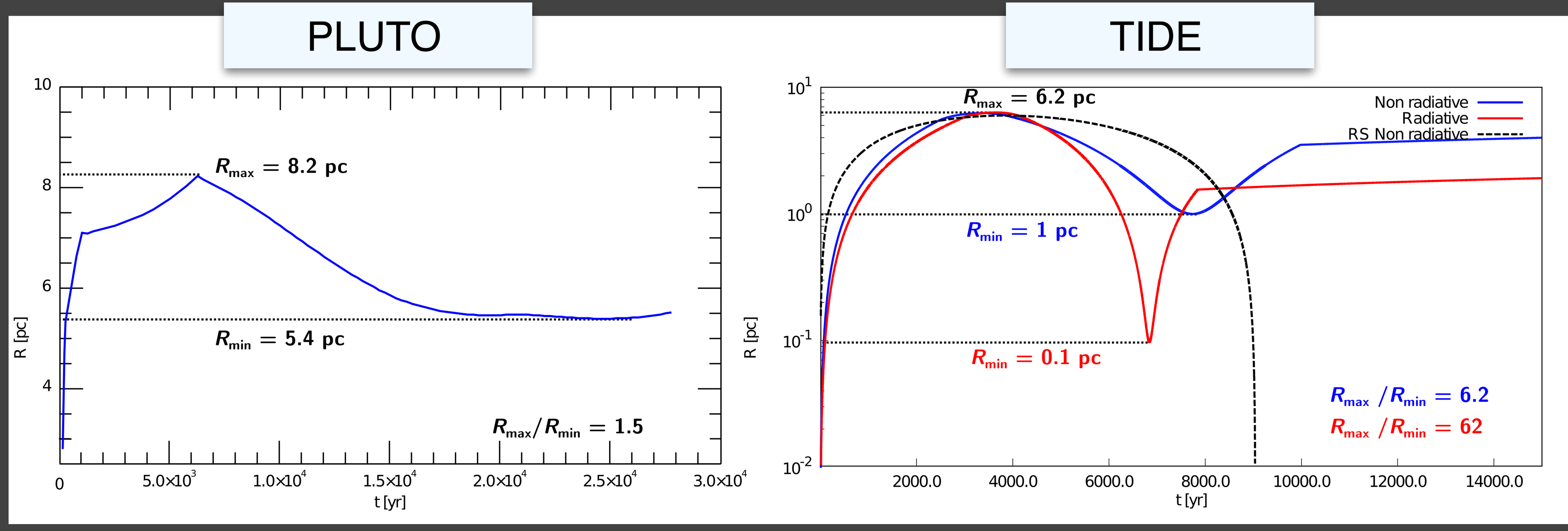
RESULTS

COMPRESSION FACTORS

The compression factors from all the considered models are given by R_{max}/R_{min}, with R_{max} and R_{min} the PWN radii respectively at the beginning (t_i) and at the end of the reverberation phase (t_f):



We find considerably lower compression factors than TL18. This is in large part due to the absence of the radiative losses. But the difference remains if comparing with TIDE results in the non-radiative regime, with a factor of 4 in the case of Crab (see below Figure).

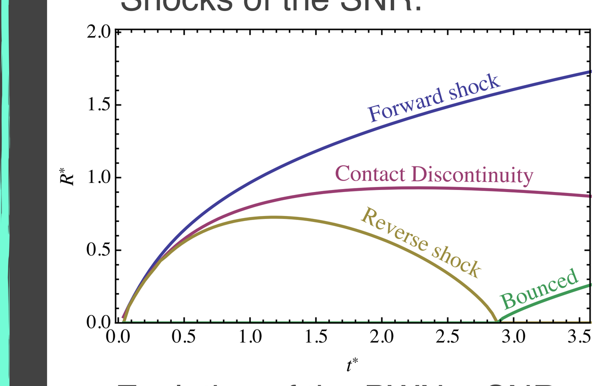


This difference is not fully understood yet and a detailed comparison of the models is ongoing. Is this because TIDE approximates on the dynamics? Or because our HD models uses a different unshocked medium assumption than our models in TIDE?

COMPLEX EVOLUTION

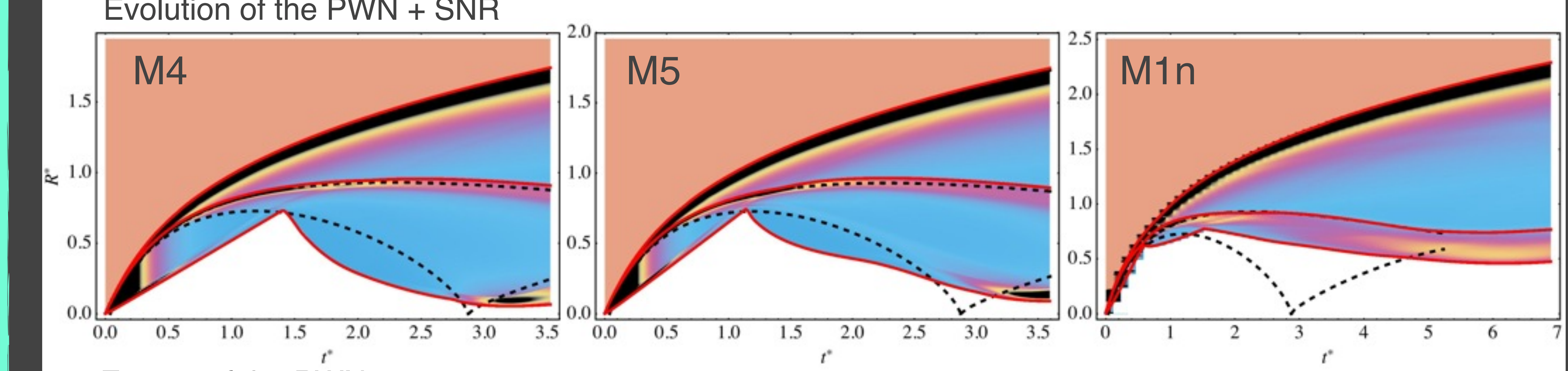
The possible evolution of the PWN during the reverberation phase is found to be more complex than expected with at least three qualitatively different evolutions for the PWN size during reverberation.

Shocks of the SNR:



Either a steady compression for low-energy PWNe, or a two-phase compression for intermediate PWNe, or just a break in the PWN expansion followed by a mild compression, for the most energetic ones. In the Figure the various behaviors are also compared with the evolution of a SNR without any PWN inside.

Evolution of the PWN + SNR



Energy of the PWN →

RADIATIVE LOSSES

While radiative losses have not been included in our calculations, their dynamical relevance can be verified "a posteriori", on our models. In a simplified way, this can be accomplished by computing the maximum energy (E_{max}) of the surviving particles to synchrotron losses, after a given evolutionary epoch, and then comparing it with the typical energy of the "break" in the energy distribution of the injected particles, namely when the energy distribution steepens from a spectral index <2 to one >2. It is found that this typically happens at E_c=10^4-10^6 $m_e c^2$.

It is found the following expression for the maximum energy:

$$E_{\rm max} = 1.25\times10^5 m_e c^2 \left(\frac{\xi}{\eta}\right)\left(\frac{E_{\rm sn}}{10^{51}\ {\rm erg}}\right)^{-1/2}\left(\frac{M_{\rm ej}}{M_\odot}\right)^{1/6}\left(\frac{\rho_{\rm ISM}}{10^{-24}\ {\rm g\ cm^{-3}}}\right)^{-2/3}$$

ξ: dimensionless factor (to be computed for each model)

η: efficiency in magnetic production (typically $0.01 \lesssim \eta \lesssim 0.1$)

Radiative losses can be more relevant at two epochs:

1. at early times: these losses may be relevant, but their main effect is to shift the effective τ_0* and L_0* for a given case.
2. during the PWN compression at reverberation: for our models we computed values for ξ in the range 0.02-0.2. Therefore, in most case neglecting radiative losses during reverberation seems justified. It should be noted that the estimation of radiative losses during the compression phase plays a sort of bootstrap effect.

FINAL REMARKS

The possible lower compression during reverberation may have important consequences on the entire evolution: the development of asymmetries may be less important; the duration of the reverberation phase and maximum luminosity achieved may change considerably. In general the understanding of the global properties of the reverberation phase may allow for an easier interpretation of the large amount of new high-energy data expected from the next generation instruments, allowing for a direct interpretation of the evolution history of aged systems.

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