STATISTICAL PROPERTIES OF THE X-RAY EMISSION FROM AGED PULSAR WIND NEBULAE

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http://arxiv.org/abs/1311.1746 for details
SKETCH OF SNR + PWN EVOLUTION

- Stellar explosion
- Expanding ejecta
- Energetic pulsar
- e+B nebula (synchrotron)
- Push on the ejecta
- Fading of the pulsar
- … and of the nebula (no more push)
- SNR reverse shock
- Reverse shock detaches
- And hits the PWN (reverberation)
- PWN squeezes and rebrightens
- Eventual fading
MODELING THE PWN EVOLUTION

PWN interacting with the outer SNR

One-zone models  e.g. Gelfand et al. 2009, Bucciantini et al. 2011

When the PWN is brighter?

- When it is very young
- At the beginning of Sedov phase **(reverberation phase)**
  PWN crushed by the SNR reverse shock, strong increase of B

Gelfand et al. 2009
A SAMPLE OF PULSAR WIND NEBULAE AT ALL AGES

Originally relatively few objects
- In radio
- Very few X-ray PWNe

Labelled as “short-lived” (up to \( \sim 10^4 \) yr)  Weiler & Panagia 1978

Change of paradigm
- A large fraction of H.E.S.S. unidentified sources are PWNe
- Follow-up campaigns in X-rays (nebula) & radio (pulsar)
- They are typically “aged” PWNs (\( \sim 10^4 - 10^6 \) yr)

Now \( \sim 70 \) objects known  e.g. Kargaltsev et al. 2013

Some intriguing statistical trends
“EVOLUTION” OF X-RAY EMISSION

Evidence for an evolution of the X-ray luminosity
- Excellent correlation with Edot
- and with PSR spin-down age

(no clear correlation in the TeV range)

PRIMARY vs SECONDARY CORRELATIONS?

Proposed explanation:
“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.”
Search for low surface brightness X-ray emission around PSRs with ages up to \( \sim 10^5 \) yr

“A systematic study of a sample of eight of these PWNe, together with Chandra data sets, has revealed that the nebulae keep expanding up to 100 kyr”

- B must decrease in time down to very low values
- Diffusion must be important (time scale for escape << PWN age)
- Anyway, large extents for old PWNe are surprising
  - They should have been crushed by the reverse shock
A DIFFERENT ... AND MAYBE MORE NATURAL KIND OF EXPLANATION

HYPOTHESIS:
the observed (Bamba et al.; Mattana et al.) correlations DO NOT outline the evolution of a “typical” PWN. They originate instead as a COMBINED EFFECT of PWNe evolving under different conditions.

THE MOST RELEVANT PARAMETERS ARE:

\[ E_{SN}, \ M_{ej}, \ \dot{E}_{o}, \ \tau_{o}, \ n_{ISM}, \ +\eta_{e}, \eta_{B} \]

ALL POSSIBLE CASES WEIGHTED WITH THEIR PROBABILITY OF DETECTION

LEADING ROLE OF \( n_{ISM} \) (>3 orders of magn. variations)
THE REVERBERATION TIME

PWN crushing (at a time $t >> \tau_o$) “reverberation”
Reverse shock. Onset of the Sedov phase

\[
\begin{align*}
M_{ej} &\sim \rho_{ISM} R_{SNR,c}^3 \\
E_{SN} &\sim M_{ej} V_{SN}^2
\end{align*}
\Rightarrow t_c \sim \left( \frac{M_{ej}^5}{\rho_{ISM}^2 E_{SN}^3} \right)^{1/6}
\]

For $M_{ej} = 8 \ M_{\text{sun}} \Rightarrow$
( primary)
dependencies on $n_{\text{ISM}}$
translate into
( secondary)
dependencies on time
(i.e. the reverberation time)
AN ANALYTIC MODEL OF THE PWN EVOLUTION

APPROXIMATE BUT GOOD FOR PARAMETRIC DEP.

- **1st Phase** ($t < \tau_0$):
  - PWN expanding in SN ejecta (flat profile)
  - constant pulsar $E_{\dot{p}}$

- **2nd Phase** ($t > \tau_0$, in free expanding ejecta):
  - asymptotic PWN linear expansion (passive)
  - asymptotically constant magnetic flux

- **Beginning of reverberation**
  - solution for 2nd Phase, evaluated at $t = t_c$

- **End of reverberation**
  - $B$ from pressure equilibrium with Sedov SNR
  - $R$ derived from magnetic flux conservation

BUT X-ray electrons can burn out before end of this phase
ON THE X-RAY LUMINOSITY

- Synchrotron basics:
  \[
  - \frac{d\gamma}{dt} = c_1 B^2 \gamma^2 \\
  \nu_{\text{sync}} = c_2 B \gamma^2
  \]

- Adiabatic vs synch-dominated evolution
- For the X-ray emitting electrons:
  \[
  t_{\text{adiab}} = \frac{R}{|\dot{R}|} \\
  t_{\text{synch}} = \frac{1}{c_1 B^2 \gamma}
  \]

- Adiabatic evolution, at \( t_{c^-} \)
- Synchrotron-dominated evolution, at \( t_{c^+} \)

Emission drops after \( t_{eq} \), when \( t_{\text{adiab}} = t_{\text{synch}} \)

Statistical Properties of PWNe - R.Bandiera - Arceti Astrobiigneté, 12 November 2013
Evolution of the synchrotron spectrum:

(cutoff rapidly moving towards lower frequencies)

$n_{\text{ISM}} = 10^{-1} \text{ cm}^{-3}$

$\log t$ (yr) ranging:
- from $4.12$ (red)
- to $4.24$ (violet)
DOES THE ADIAD. TO SYNCH. TRANSITION OCCUR?

- If PWN X-ray emission switches off at $t_{eq}$ (when $t_{adiab}=t_{synch}$) $R_{eq}$ independent of $n_{\text{ISM}}$! ... and therefore also on $t_c$
  - Bamba et al. empirical relation cannot be reproduced!!
- Dependence on $n_{\text{ISM}}$, instead, if X-ray emitting electrons are adiabatically dominated all the way, until $t_{c+}$.

$$R_{\text{PWN}}(t_c+) \propto \rho_{\text{ISM}}^{-1/4}$$

- A “fictitious” time dependence

$$R_{\text{PWN}}(t_c+) \propto t^{3/4} \propto \dot{E}^{-3/8}$$

This because:

$$\rho_{\text{ISM}} \sim \frac{M_{\text{ej}}^{5/2}}{E_{\text{SN}}^{3/2}} t^{-3} \sim \frac{M_{\text{ej}}^{5/2}}{E_{\text{SN}}^{3/2}} \frac{\dot{E}^{3/2}}{(E_0 \tau_{\text{dyn}}^2)^{3/2}}$$

(Edot dependence assumes magnetic-dipole spin-down law)
Two regimes:
- $t_{eq} < t_{c+}$ \hspace{1cm} $R_{\text{PWN}} = \text{const}$ horizontal branch
- $t_{eq} > t_{c+}$ \hspace{1cm} $R_{\text{PWN}} \propto t^{3/4}$ \hspace{1cm} in agreement with Bamba et al.

Absolute positioning of the lines is not accurate, and dependent on model details.
X-RAY EMISSION

• Compute $L_{\text{synch}}$ in Phase 2
  (adiab.regime + $\alpha \approx 2$ power-law @ injection)

$$L_{\text{synch}} \propto \frac{1}{R^3 t} \propto \rho_{\text{ISM}}^{4/3} \quad \text{at} \quad t = t_{c-}$$

• Evolution for $t_{c-} < t < t_{eq}$ (compression in adiab.regime)

$$L_{\text{synch}} \sim L_{\text{synch},c-} \left(\frac{R_{c-}}{R}\right)^4$$

• If still in adiabatic regime at $t_{c+}$

X-RAY SPECTRAL INDEX

IF NEGLIGIBLE SYNCH. LOSSES, HARDER SPECTRA

- Gotthelf 2003
  - Correlation between PSR and PWN X-ray spectral index
  - Both decrease with $\tau$ (and increase with $E_{\text{dot}}$)

- Li et al. 2008
  - They do not confirm correlation between $\Gamma_{\text{PSR}}$ and $\Gamma_{\text{PWN}}$.
  - CONFIRMED instead time dependence of $\Gamma_{\text{PWN}}$ (two bunches?)

SUMMARY

• Simplified model for the evolution of old PWNe (but still inside the associated SNR)

• Working hypothesis: observed X-ray correlations as a combined effect of objects evolving in different ambient densities

• Assumption: aged PWNe are best detected near reverberation time

RESULTS:

- $R_{\text{PWN}}(t)$
- $L_X(\dot{E})$
- Harder X-ray spectra for older PWNe

Even after reverse-shock compression, the evolution of X-ray emitting electrons must be adiabatically dominated