Theory of Pulsar Wind Nebulae

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Del Zanna, Volpi, Amato, Olmi, Arons, Komissarov, Camus

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Madrid, Spain, 2013
Pulsar Wind Nebulae

**PWN** once upon a time - Once they were the Crab Nebula, and systems like it

**PWN** now - Anything that traces the interaction of a PSR (NS) with the environment
Modeling Elements

**Dynamics** - Wind confinement, Nebular flow structure and geometry, Evolutionary effects

**Acceleration** - Particle spectrum, Injection properties

**Emission** - Particles evolution, Magnetic field distribution, Radio

**Extras** - Short timescale variability Flares
A case for MHD

Why an MHD description?
A case for MHD

Why an MHD description?  MHD is “simple”
A case for MHD

Why an MHD description?

MHD is “simple”

Larmor radii \ll nebular radius (advective regime)
Energy losses are negligible (radio particles dominate)
Almost pure pair plasma (no dispersive effects)
Interested in long evolutionary timescales
Why an MHD description?

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Larmor radii \( \ll \) nebular radius (advective regime)
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Particles are accelerated with high efficiency
Theoretical model for PWNe - 1-D steady-state (Rees & Gunn 1974; Kennel & Coroniti, 1984) and self-similar (Emmering & Chevalier, 1987) - free expansion phase.

Basic assumptions:

- The wind terminates with a strong MHD shock
- Particles are accelerated at TS
- Relativistic MHD flow in the PWN region
- Synchrotron losses inside the nebula
- Wind parameters derived by comparison with observations:

\[
R_{TS} = 3 \times 10^{17} \text{ cm, } \quad L = 5 \times 10^{38} \text{ erg/s, } \quad \gamma = 3 \times 10^6, \quad \sigma = 3 \times 10^{-3}
\]
Global properties 1D

RADIO

OPTICAL

X-RAYS

Global morphology

Polarization

General evolution

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Evolution 1D

- “Free expansion”
  - Duration $T \sim 10^{3-4}$ yr
  - Constant pulsar energy input - Emission at high energies
- Reverberation -
  - $T \sim 10^4$ yr
  - Enhanced emission due to re-energization
- Sedov -
  - $T \sim 10^5$ yr
- Bow-Shock - interaction with the ISM

(van der Swaluw et al. 2001, 2005; Bucciantini et al. 2003, 2005)
Fine structures

- Vela pulsar (*Helfand et al.*, 2001; *Pavlov et al.*, 2003)
Wind models 2D

RMHD (Bogovalov 2001, Komissarov 2006, Bucciantini et al. 2006)

Lorentz factor \( \sim \sin(\theta) \)
Energy flux \( \sim \sin^2(\theta) \)
Dynsmics 2D

- Initial magnetic field with a narrow equatorial neutral sheet
- Dissipation in a striped wind
Fine structures
Fine structures

3C58

G11.2

B1509

G21.5

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3D - Final Solution?

3D allows for higher sigma

Inner region still axisymmetric - toruslike

Weaker jet?  Polarization?
Reverberation - Crushing by the SNR Reverse Shock

Evolution 2D

Relic PWNe

SNR G327.1-1.1, Gaensler & van der Swaluw (2004)
Evolution 2D

- Most pulsars kick velocity is supersonic in ISM
- Forward shock visible in Hα
- PWN visible as a radio and X-rays tail

PSR B1957+20 (Stappers et al. 2003)

Bucciantini et al. 2005
**Acceleration: Pair Plasma**

**Perpendicular relativistic shock - Superluminal**

- Maxwellian at low energies
- Evidence for non-thermal tail only for subluminal shock

![Graphs showing particle spectra under different obliquities and times](Spitkovsky 2006)

- Evidence for non-thermal tail only for subluminal shock
- Maxwellian at low energies

**Spitkovsky 2006**
Reconnection in a striped wind produces hard spectra - $N(E) \sim E^{-1}$

The hard spectrum extends for an energy range from $\gamma_{min} = \gamma_0$ to $\gamma_{max} = \gamma_0 \sigma^{1/(2-p)}$

High magnetization $\sigma \geq 30$ and multiplicity $\geq 10^8$
Low $\gamma_0 \sim 10$

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For all PWNe where a broad band spectrum is available we see a broken power-law:

- a hard part in IR/Radio - $N(E) \sim E^{-1} E^{-1.5}$
- a soft part in Optical - $N(E) \sim E^{-2} E^{-2.5}$
- a cooled component in X

Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Crab</th>
<th>3C58</th>
<th>B1509-58</th>
<th>Kes 75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of the ejecta ($M_\odot$)</td>
<td>$M_{ej}$</td>
<td>$3.0 \pm 0.3$</td>
<td>$2.6 \pm 0.2$</td>
<td>$2.8 \pm 0.1$</td>
<td>$3.2 \pm 0.2$</td>
</tr>
<tr>
<td>Initial pulsar luminosity ($10^{38}$ erg s$^{-1}$)</td>
<td>$L_{p0}$</td>
<td>$3.0 \pm 0.1$</td>
<td>$3.0 \pm 0.1$</td>
<td>$3.0 \pm 0.1$</td>
<td>$3.0 \pm 0.1$</td>
</tr>
<tr>
<td>Braking index</td>
<td>$\alpha$</td>
<td>$2.3 \pm 0.1$</td>
<td>$2.3 \pm 0.1$</td>
<td>$2.3 \pm 0.1$</td>
<td>$2.3 \pm 0.1$</td>
</tr>
<tr>
<td>Low-energy injection index</td>
<td>$\beta$</td>
<td>$2.5 \pm 0.1$</td>
<td>$2.5 \pm 0.1$</td>
<td>$2.5 \pm 0.1$</td>
<td>$2.5 \pm 0.1$</td>
</tr>
<tr>
<td>High-energy injection index</td>
<td>$\gamma$</td>
<td>$1.8 \pm 0.1$</td>
<td>$1.8 \pm 0.1$</td>
<td>$1.8 \pm 0.1$</td>
<td>$1.8 \pm 0.1$</td>
</tr>
<tr>
<td>Fraction of magnetic energy</td>
<td>$\eta$</td>
<td>$0.1 \pm 0.05$</td>
<td>$0.1 \pm 0.05$</td>
<td>$0.1 \pm 0.05$</td>
<td>$0.1 \pm 0.05$</td>
</tr>
<tr>
<td>Fraction of luminosity that goes into pairs</td>
<td>$\eta_{pair}$</td>
<td>$0.5 \pm 0.1$</td>
<td>$0.5 \pm 0.1$</td>
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<td>$0.5 \pm 0.1$</td>
</tr>
<tr>
<td>Fraction of luminosity that goes into ions</td>
<td>$\eta_{ion}$</td>
<td>$0.53 \pm 0.05$</td>
<td>$0.53 \pm 0.05$</td>
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</tr>
<tr>
<td>Fraction of supernova explosion energy</td>
<td>$\xi$</td>
<td>$0.005 \pm 0.002$</td>
<td>$0.005 \pm 0.002$</td>
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<tr>
<td>Spin-down time ($yr$)</td>
<td>$\tau$</td>
<td>$10^{39}$</td>
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<tr>
<td>Age ($yr$)</td>
<td>$t_\nu$</td>
<td>$10^{4}$</td>
<td>$10^{4}$</td>
<td>$10^{4}$</td>
<td>$10^{4}$</td>
</tr>
<tr>
<td>ISM density (cm$^{-3}$)</td>
<td>$\rho$</td>
<td>$10^{-4}$</td>
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<tr>
<td>ISM velocity (km s$^{-1}$)</td>
<td>$v$</td>
<td>$10^{3}$</td>
<td>$10^{3}$</td>
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<tr>
<td>Peak energy ratio</td>
<td>$\nu_{p}$</td>
<td>$10^{1}$</td>
<td>$10^{1}$</td>
<td>$10^{1}$</td>
<td>$10^{1}$</td>
</tr>
<tr>
<td>Braking index</td>
<td>$w$</td>
<td>$10^{2}$</td>
<td>$10^{2}$</td>
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Making what we see 1D

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The break Lorentz factor is of order $10^5$

How do we form a broken power-law?
What sets the break?
Is there a Maxwellian component?
What is the wind multiplicity?
Making what we see 2D

- Main torus
- Inner ring (wisps structure)
- Knot
- Back side of the inner ring (Anvil)

No jet - Axisymmetric assumption

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Making what we see 2D
Making what we see 2D
Radio particles 2D

\[ \Delta \delta \text{ (arcsec)} \]
\[ \Delta \alpha \text{ (arcsec)} \]

Bandiera et al 02

Olmi et al in prep
Time variability - wisps

- Wisp moving outward
- Year long limit cycle
- Variability in the knot
- Bubble in the jet $v \sim 0.6 \, c$

Variability in the knot structure
Jet feature moving at $0.6 \, c$

Local instabilities or global modes?

Slane 05, DeLaney 06
Instability of the shear layers creates eddies at the rim shock

Eddies are advected outward and a toroidal pressure wave is launched

There is no wave reflection from the boundary

Waves reflected on the axis modulate the TS shape

The equatorial channel is kink unstable
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Wisps speed

There is a general tendency for a 'standing' outgoing wave pattern. The Plot show the X-ray luminosity, based on the pictures represent the X-ray luminosity at three...
Wisps speed

As a general tendency for an outgoing wave pattern.

Variability of the wisps in the Crab Nebula has been known since the first high resolution observations [45, 46], and there is evidence for variability of the main knotted structure since the early 1970s [71, 72]. Variability of the wisps in the Crab Nebula has been observed also in the knot 23 by Herrington et al. [70, 59], and B1509 [31]. B1509 shows also variability in the jet, which usually results from a pure fluid picture: electrons are compresses by a strong magnetic field.

The strong magnetic hoop stress in these layers stops the outflow and turns it back towards the axis. The resultant axial compression drives the polar jets in a fashion reminiscent of the tooth-paste flow. The axial pinch is rather non-uniform and the flow structure at the jet axis is dominated by large gaps imposed by sun constraints. The unit for the color scale are $\sim 10^8$ cm.

Outgoing velocity is lower in the torus than in the jet. The fire-hose instability [84] in the case of Vela. On the other hand, the fire-hose instability [84] in the case of Vela does not take into account the energy flux anisotropy, and the resulting wave pattern is significantly different than the one observed in Vela. Variability in the jet, which usually results from the shock of two different instants. Notice the bright features moving outwards, and there is a general tendency for an outgoing wave pattern.

The two panels compare the radial evolution of the wisp region, they introduce a substantial deviation from a pure fluid picture: electrons are compresses by a strong magnetic field.

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Flares

Not from pulsar:
- flares are not pulsed or in phase
- no variations in the timing residual

Sept. 2010 flare

April 2011 Flare Spectrum
- Flare spectrum: Power law (index 1.6), exponential cut-off at 580 MeV
- Pulsar-like, but no sign of pulsations in flare photons.
- 5 times brighter than previous flare (from Rolf Bueler and the Fermi LAT team)
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Unlikely MHD origin like the slow variability of the wisps:
- MHD effects are achromatic
- size of the accelerator is very small (day-light)
- unlikely high magnetic field

Electrostatic acceleration?

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Summary and conclusions

MHD model is successful in reproducing the **persistent features**

3D model promising to solve the **sigma problem**

Unsolved issue in particles acceleration and the **origin of radio electrons**

MHD variability due to unstable Termination Shock can act as a **source of turbulence from larger scales** into the nebula (as opposed to self generated turbulence at the shock)

Very **short dynamics** (flares) and turbulence long overlooked
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Thank you