Physics of pulsar winds

Yuri Lyubarsky
Ben-Gurion University, Israel
Pulsar magneto sphere

Pulsar wind

e^+ , e^-, (ions?)

electro-magnetic fields

Termination shock

Pulsar wind nebula

1000 km

0.1 pc

2-3 pc
Energy budget

Relativistic pair-plasma outflow on open field lines

\[ P \approx I \Omega \dot{\Omega} \]

Radio emission < 1%
Gamma-emission 1-10%
Pulsar wind 90-100%

\[ P \approx \frac{1}{c^3} \mu^2 \Omega^4 \]

\[ \approx 6 \cdot 10^{31} \frac{B_{12}^2}{P^4} \text{ erg/s} \]
Pulsar wind

Pulsars eject relativistic $e^+e^-$ plasma.

The induction electric field is shielded by the plasma if $n > n_{GJ} = \frac{B}{ceP}$.

Then the magnetic field is frozen into the plasma; the MHD flow.

Theoretical estimates of the pair multiplicity are quite uncertain (e.g. Hibschman & Arons ‘01; Timokhin ‘10). Observations of PWNe yield $\kappa = n/n_{GJ} > 10^5$ (de Jager ‘07).

In any case, the plasma energy is small as compared with the magnetic energy.

$$\sigma \equiv \frac{\text{Poynting flux}}{\text{Kinetic energy flux}} \gg 1$$

How is the electromagnetic energy transformed into the plasma energy?
Rotation twists up field into toroidal component, slowing rotation
In the far zone, the field becomes predominantly azimuthal

\[ P_{\text{Poynting Flux}} = \frac{B_\varphi^2}{4\pi} c \]
Wind from obliquely rotating magnetosphere: variable fields are propagated as waves

At the equator, $\langle B \rangle = 0$
Current sheet separating oppositely directed fields

Split monopole
(Bogovalov ‘99)

Dipole magnetosphere
(Spitkovsky ‘05)
Pulsar wind and pulsar wind nebula

Ram pressure balance: $r_s \sim 0.1 r_n$

PWN (shocked pulsar wind)

termination shock

pulsar wind

Crab nebula
The so called $\sigma$-problem

There is a pervasive belief that when the pulsar wind arrives at the termination shock, $\sigma$ is already as small as 0.003. Oh, dear! How can we pass from a high $\sigma$ ($\sim 10^4 - 10^6$) close to the pulsar to $\sigma$ that low at the shock?

All the available observation limits on $\sigma$ (Kennel & Coroniti ’84 and others) are obtained from the analysis of the plasma flow and radiation beyond the termination shock. Extremely small $\sigma$ was obtained at the assumption that the flux of azimuthal field is conserved. Then $\sigma$ increases $\sim 10$ times at the shock (compression ratio 3) and $\sim (r_{\text{nebula}}/r_{\text{shock}})^2$ $\sim 100$ times more when filling the nebula so that $\sigma<1$ within the nebula requires $\sigma\sim 0.001$ upstream of the shock.

But: 1. These estimates could be relevant (at best) only to the mean field; alternating fields do not survive within the nebula ($r_{\text{Larmor}} \gg r_L = c/\Omega$).
   2. Moreover, the mean field does not remain azimuthal within the nebula.
What fraction of the total energy is transferred by the mean field?

All MHD outflows have a hollow cone energy distribution because $B_\phi = 0$ at the axis. In pulsar winds, most of the energy is transferred along the equatorial belt. This energy is transferred by alternating fields.

\[ \text{Poynting flux} = \frac{B_\phi^2}{4\pi} c \]

Angular distribution of the energy flux (according to Spitkovsky’s model of pulsar magnetosphere)
What fraction of the total energy is transferred by the mean field?

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Angular distribution of the energy flux (according to Spitkovsky’s model of pulsar magnetosphere)

<table>
<thead>
<tr>
<th>Inclination angle, $\alpha$</th>
<th>Ratio of energy fluxes mean/alternating, $\tilde{\sigma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$30^\circ$</td>
<td>0.39</td>
</tr>
<tr>
<td>$45^\circ$</td>
<td>0.1</td>
</tr>
<tr>
<td>$60^\circ$</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Dissipation of alternating magnetic field is the main energy transformation mechanism in pulsars.

The questions under discussion: where and how do the waves decay?
Magnetic dissipation in the striped wind

Current starvation mechanism
(Usov ‘75; Michel ‘82, ‘94; Coroniti ‘90; L & Kirk ‘01; Kirk & Skjæraasen ‘03; Zenitani & Hoshino ‘07)

\[ B \propto \frac{1}{r} \quad j \approx \frac{B}{\lambda} \propto \frac{1}{r} \]

\[ n \propto \frac{1}{r^2} \quad V_{\text{current}} \propto \frac{j}{en} \propto r \]

Dissipation when \( v_{\text{current}} \sim c \)

The dissipation scale is comparable or larger than the termination shock radius (\( \sim 0.1 \) pc). The mechanism works marginally OK.
If the alternating fields survive until the flow arrives at the termination shock

The flow is sharply compressed at the shock driven dissipation within the shock structure

(L ‘03, 05; Petri & L ‘07; Sironi & Spitkovsky ‘11)

MHD flow beyond the termination shock is determined only by the total energy flux and by the mean magnetic field in the wind independently of where the alternating fields annihilated. Therefore the morphology of PWN is independent of where the alternating fields annihilated. The microphysics (particle acceleration) does depend (L ‘03; L & Liverts ‘08; Sironi & Spitkovsky ‘11).
Variable but non-alternating fields

At high latitudes, the field does not change sign. Variable fields propagate as fast magnetosonic waves.

These waves decay via non-linear steepening and formation of multiple shocks (L ‘03).
The fate of the mean field

The mean field transfers a small fraction of the total energy but still larger than spherically and axisymmetrical models demand.

This is because the expansion of coaxial magnetic loops within the nebula implies an increase in the magnetic field strength with radius and the field within the nebula could exceed the equipartition value unless the magnetization at the termination shock is extremely small.

The problem can be alleviated if the kink instability destroys the concentric field structure in the nebula (Begelman ‘98). Then the loops could come apart and the mean field strength is not amplified much by expansion of the flow.
Kink instability in a relativistically hot column confined by an azimuthal magnetic field (Mizuno et al ‘10)
(a) $p_{\text{gas}}$

(b) $B_x$

$\text{time} = 6.00$
Toroidal magnetic loops come apart and the pressure difference across the nebula is washed out. Therefore, elongation of a PWN cannot be correctly estimated by axisymmetric models. Previous dynamical arguments concluding that $\sigma$ must be extraordinarily small can be abandoned.
No mechanism is known for dissipation of alternating fields at the scale $\sim 10^{11} - 10^{13}$ cm. Dissipation at the bow shock.
PSR 1957+20 and PSR 1259-63: X-ray emission from the shocked plasma implies efficient dissipation of the Poynting flux.

Double pulsar PSR J0737-3039. Modulation of the radio emission from B with the period of A implies that alternating fields in the wind from A are not erased completely.

Making use of theoretical criteria for shock dissipation, one can place limits on the parameters of the winds in these systems. According to 1D model (Petri & L ‘07):

- \( \kappa > 300 \) in PSR J0737-3039
- \( \kappa < 10^4 \) in PSR 1957+20
- \( \kappa < 8 \times 10^4 \) in PSR 1259-63

These estimates should be modified according to the results of 3D simulations (Sironi & Spitkovsky ‘11)
Perspectives of direct observations of pulsar winds

1. Pulsed radiation from the far zone

Pulses are observed if

\[ R < 2\pi \Gamma^2 R_L \]

Arons ‘79; Kirk et al ‘02; Petri & Kirk ’05, Petri ‘08
2. Probing pulsar winds using inverse Compton scattering

A line-like bulk Comptonization component from the pulsar wind in the gamma band is predicted for the binary pulsar system PSR B1259-63 (Ball & Kirk ‘00; Ball & Dodd ‘01; Khangulyan et al. ‘07, ‘11; Petri & Dubus ‘11).

Spectrum of IC radiation from the pulsar wind in PSR B1259-63 (Khangulyan et al. ‘11)
Conclusions

1. Pulsars lose their rotational energy on generation of the relativistic, magnetized wind. The energy transport is dominated by Poynting flux.

2. Most of the energy is transferred in the equatorial belt by alternating magnetic fields. Therefore dissipation of alternating fields is the main energy conversion mechanism.

3. The mean field is maximal at intermediate latitudes.

4. MHD flow beyond the termination shock is determined only by the total energy flux and by the mean magnetic field in the wind. The morphology of PWN is independent of where the alternating fields annihilated. Bucciantini’s talk.

5. Magnetic dissipation strongly affects the particle acceleration. This opens a new way to understanding spectra of PWNe. Sironi’s talk.