Pulsar magnetosphere

Pulsar wind

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

electro-magnetic fields

Pulsar wind nebula
The hoop stress

Magnetic hoop stress \( F = \frac{1}{c} j \times B \)

Total force \( F = \rho_e E + \frac{1}{c} j \times B \)
\( E + \frac{1}{c} v \times B = 0 \)

As \( v \to c \) the electric and magnetic forces nearly cancel each other.
In the far zone, the magnetic field is nearly azimuthal
Obliquely rotating magnetosphere
How the electromagnetic energy is transformed into the plasma energy?

Non-oscillating fields: no energy release mechanism

Waves: various dissipation mechanisms


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

\[ n \propto \frac{1}{r^2} \quad v_{\text{current}} \propto \frac{j}{n} \propto r \]
Observations suggest that the energy flows from the pulsar predominantly within the equatorial belt.

What theory says about the angular distribution of the energy flux in the pulsar wind?
Split monopole solution
Michel (1973) – aligned rotator
Bogovalov (1999) – oblique rotator

\[ f_w = \frac{f_0}{r^2} (\sin^2 \theta + \frac{1}{\sigma_0}), \]
In the equatorial belt, most of the energy is transferred by alternating electro-magnetic field.
The fate of the alternating field


2. Dissipation at the termination shock: driven reconnection (Lyubarsky, in progress)
The shock in a striped wind (1.5D PIC simulations)

\[ \gamma = 7 \]

\[ \sigma = 2.5 \]

\[ N = 2 \times 400,000 \]
MHD flow beyond the termination shock is determined only by the total energy flux and the mean magnetic field in the wind.
The mean field=0 at the equator and at the axis
Origin of the get-torus structure (Lyubarsky 2002)

magnetic collimation

disk

termination shock

disk
MHD simulations of the pulsar wind nebula
Komissarov & Lyubarsky 2003

\[ f_w = \frac{f_0}{r^2} (\sin^2 \theta + \frac{1}{\sigma_0}); \]

\[ B = \sqrt{\frac{4\pi f_0 \xi}{c r}} \sin \theta \left(1 - \frac{2\theta}{\pi}\right); \quad \xi \leq 1 \]

\[ \sigma = 0.1 \xi^2 \]
Pulsar plasma fills in the cavity within the expanded cold envelope

magnetic field and velocity

expansion velocity
5000 km/s

\[ \xi = 0.3 \]
\[ \sigma = 0.009 \]
Gas pressure and velocity field around the termination shock

towards the observer

- sprite
- rim shock
- bright arch
- fluff
- --DISK---
- termination shock
- Mach belt

\( c \)
Magnetic pressure/gas pressure
Simulated images

σ=0.004

σ=0.009

σ=0.025
Simulated image, $\sigma=0.009$, with magnetic field at the axis
Chandra image of the Crab Nebula

Bright Arch

Polar Jet

fluff

Counterjet
Particle acceleration at the termination shock in a striped wind
Radio emitting electrons are accelerated now in the same region as the ones responsible for optical to X-ray emission (Gallant & Tuffs; Bietenholtz, Frail & Hester)
Difference image at 4615 MHz (1998 Aug 9-Oct 13)
\[ N(E) = KE^{-1.6} \text{ from } E_{\text{min}} \leq 100\text{MeV} \text{ to } E_{br} \approx 1 \text{ TeV} \]

\[ N = \int N(E)\,dE = \frac{K}{0.6}E_{\text{min}}^{-0.6} \quad \varepsilon = \int EN(E)\,dE = \frac{K}{0.4}E_{br}^{0.4} \]

Particle acceleration in the standard (kinetic energy dominated) shock

Fermi acceleration at ultra-relativistic shocks: \[ N(E) = KE^{-(2.2 \div 2.3)} \]

(Bednarz & Ostrowski 1998; Gallant & Achterberg 1999; Kirk, Guthman, Gallant & Achterberg 2000)

\[ \Gamma \approx 100; \quad \dot{N}_p \approx 10^{39} \text{ s}^{-1}; \quad \dot{N}_{e^\pm} \approx 10^{40} \div 10^{41} \text{ s}^{-1} \]

\[ \dot{N}_{GJ} = 3 \cdot 10^{34} \text{ s}^{-1} \]

2. Lyubarsky (2003): Dissipation of the Poynting flux at the termination shock
Conclusions

1. Most of the energy is transferred in the equatorial belt by alternating magnetic fields

2. Magnetization of the postshock flow is determined only by the mean magnetic field (=0 at the equator)

3. Termination shock is highly non-spherical

4. The jet is formed beyond the termination shock
Unsolved problems

1. Azimuthal symmetry of the internal ring.

2. Wisps

3. Flat spectrum of the radio emitting electrons
\[ r_L = \frac{\varepsilon}{eB} \]

\[ \delta \approx \sqrt{\frac{\varepsilon_{\text{max}}}{eB_0}} \]

\[ E = \frac{v}{c} B \propto \varepsilon \]
Crab’s jet

(a) Chandra
(b) HST difference image

Bow wave