Magnetohydrodynamics of pulsar winds and plerions

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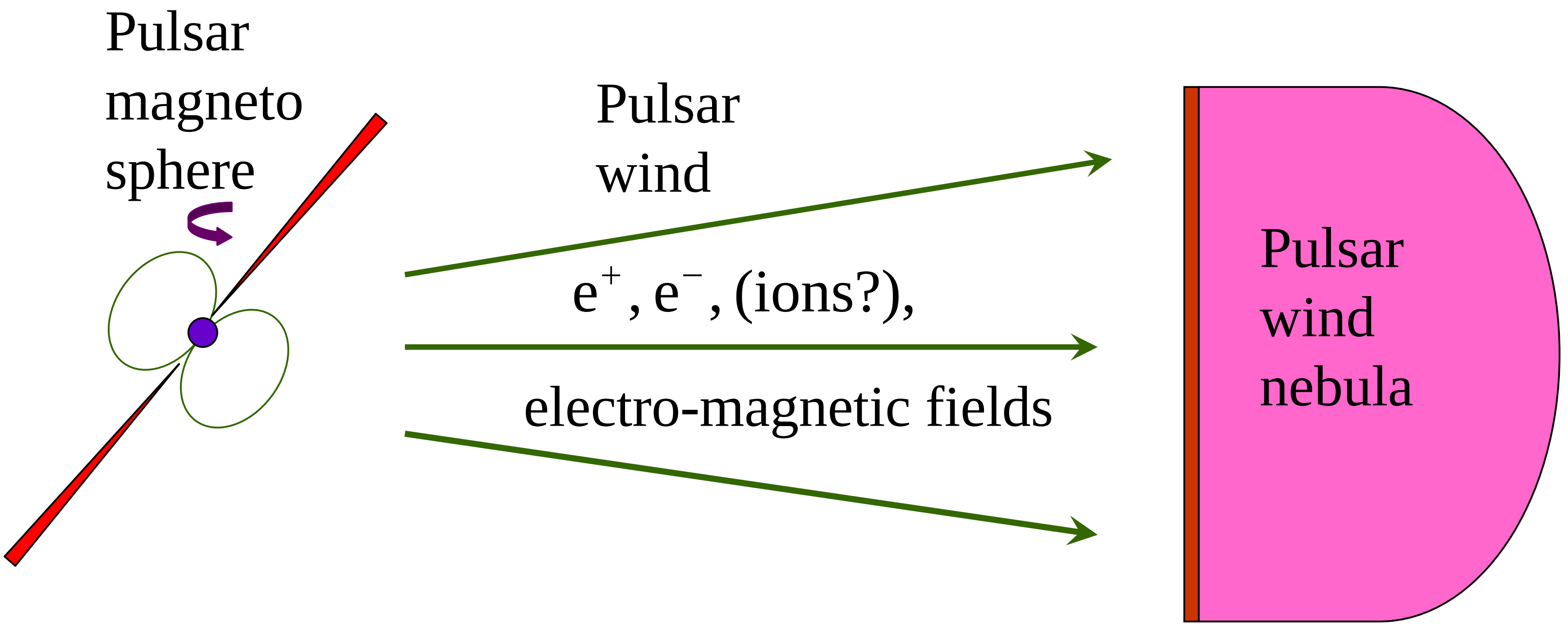
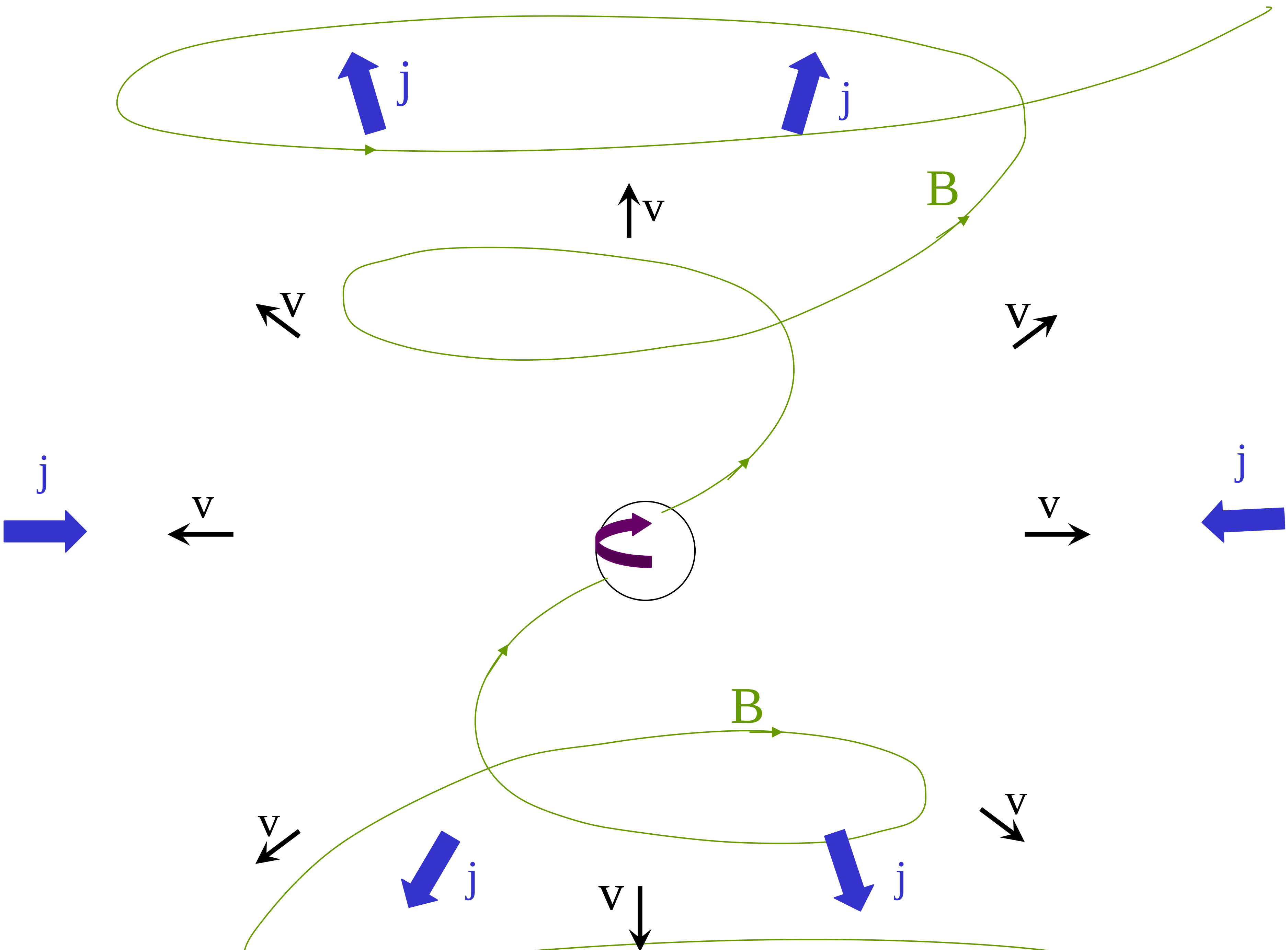

Pulsar
magneto
sphere
Pulsar
wind
e+, e−, (ions?),
electro-magnetic fields
Pulsar
wind
nebula


j
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v
B
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j
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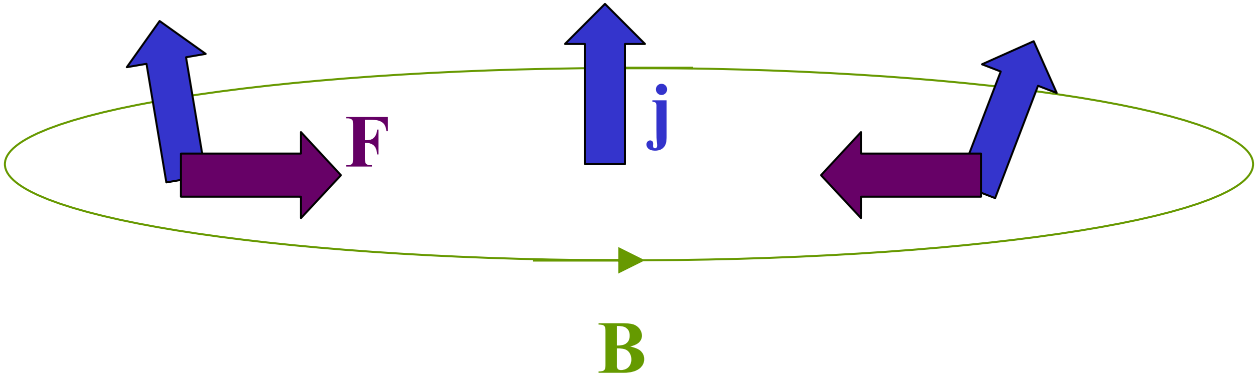
v
j
v
j

The hoop stress

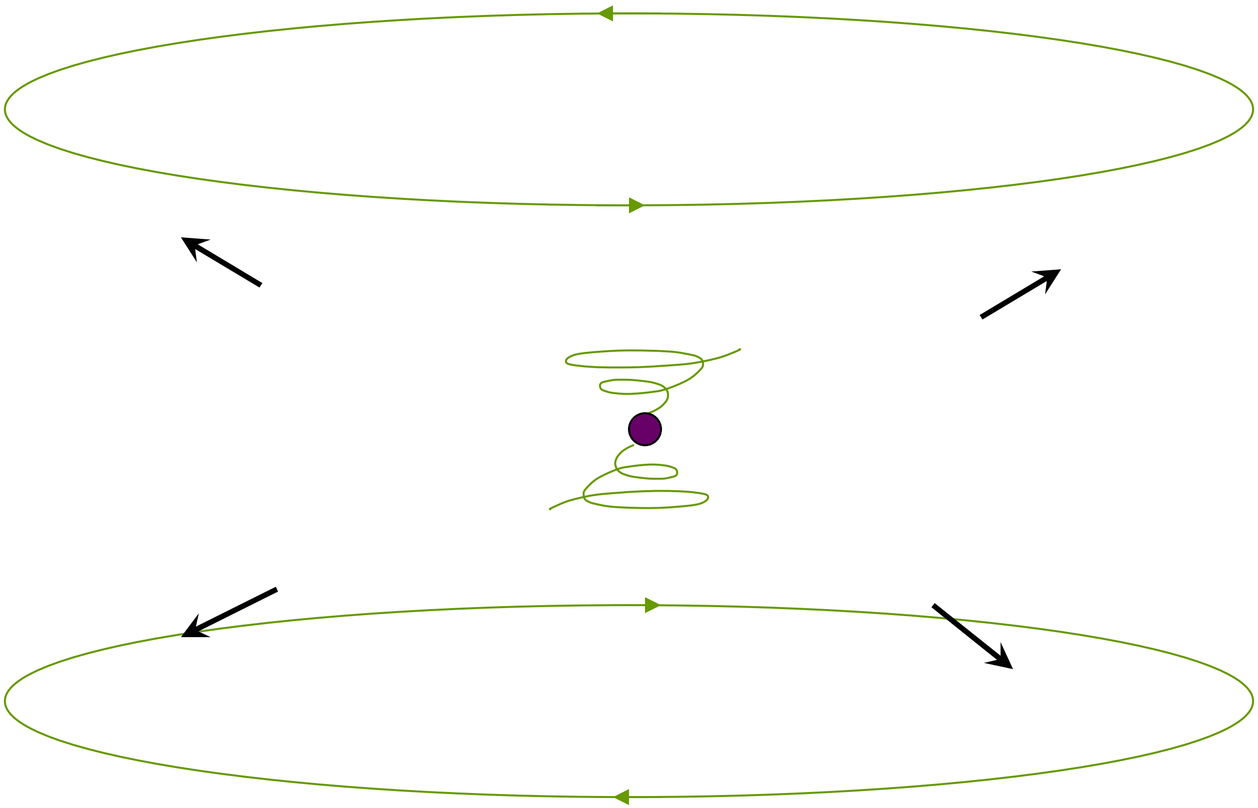


Magnetic hoop stress $\mathbf{F} = \frac{1}{c}\,\mathbf{j}\times\mathbf{B}$

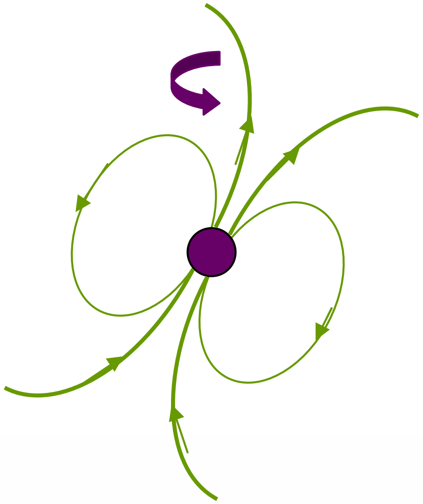
Total force $\mathbf{F} = \rho_e \mathbf{E} + \frac{1}{c}\,\mathbf{j}\times\mathbf{B}$ $\mathbf{E} + \frac{1}{c}\,\mathbf{v}\times\mathbf{B} = 0$

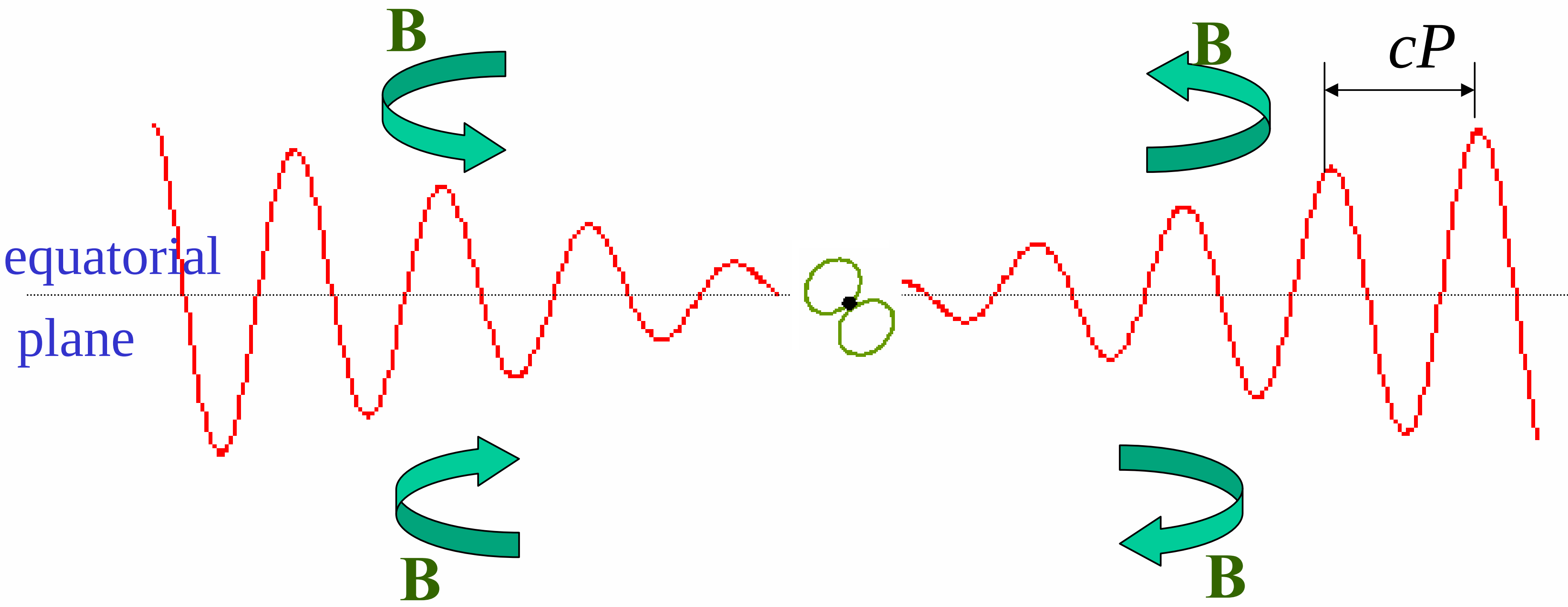
As $v \to c$ the electric and magnetic forces nearly cancel each other

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

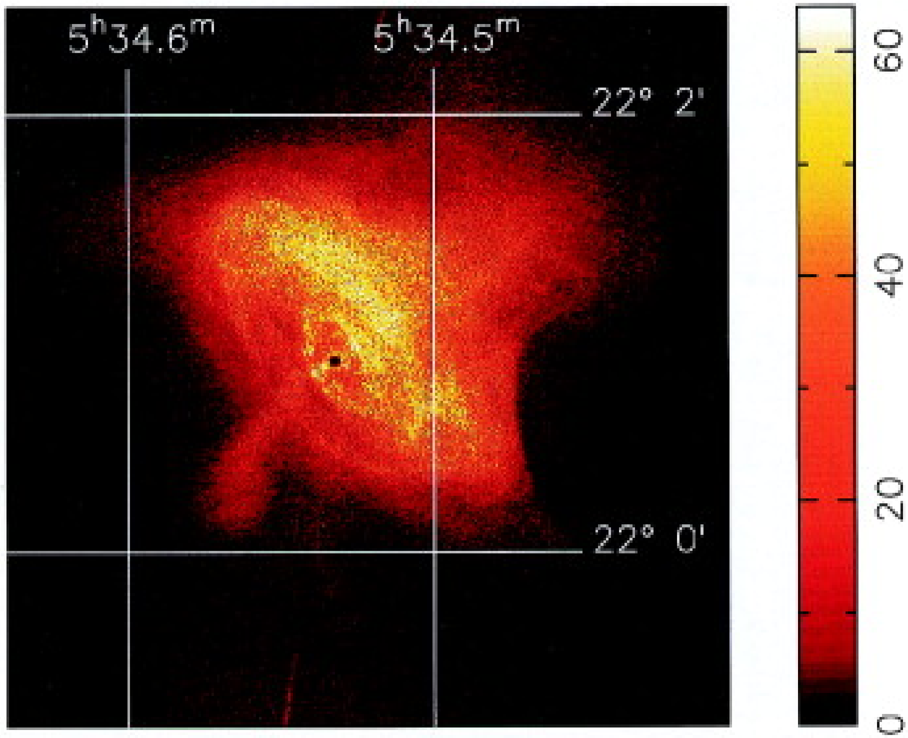
Waves: various dissipation mechanisms

(Usov 1975; Michel 1982, 1994; Coroniti 1990; Melatos & Melrose 1996; Lyubarsky & Kirk 2001; Lyubarsky 2003; Kirk & Skjaeraasen 2003; Melatos & Skjeraasen 2004)

$$B \propto \frac{1}{r} \qquad j \approx \frac{B}{\lambda} \propto \frac{1}{r}$$

$$n \propto \frac{1}{r^2} \qquad v_{\text{current}} \propto \frac{j}{n} \propto r$$

Observations suggest that the energy flows from the pulsar predominantly within the equatorial belt



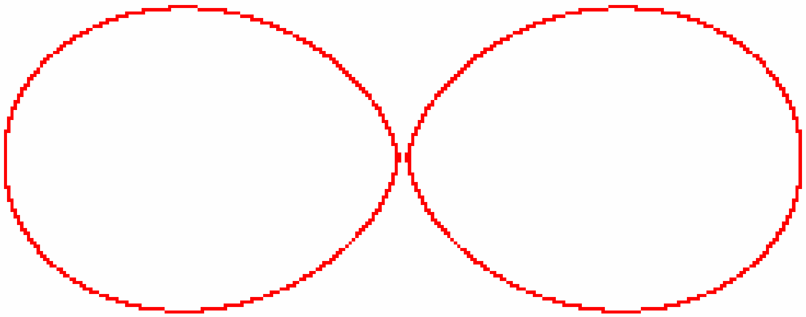
What theory says about the angular distribution of the energy flux in the pulsar wind?

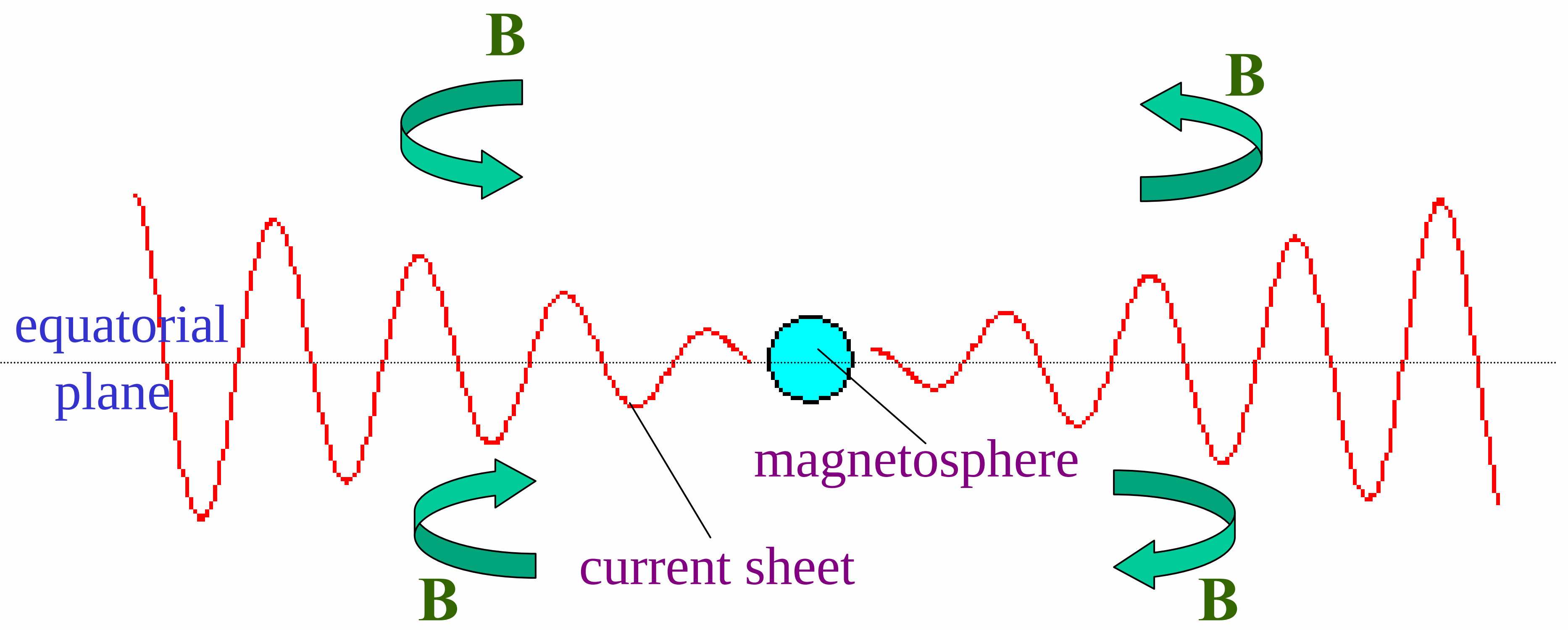
Split monopole solution

Michel (1973) – aligned rotator

Bogovalov (1999) – oblique rotator

$$f_w = \frac{f_0}{r^2}\left(\sin^2\theta + 1/\sigma_0\right),$$





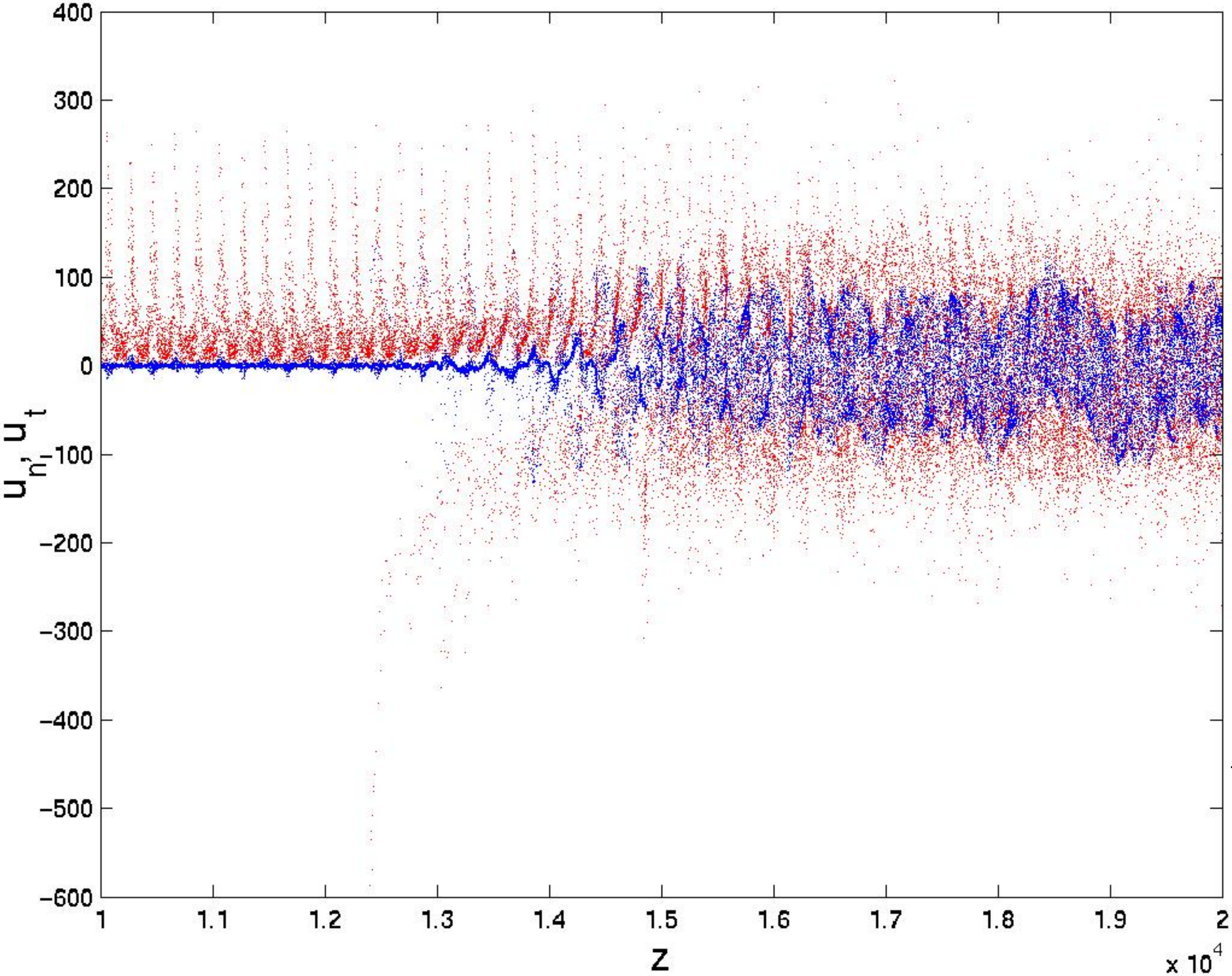
In the equatorial belt, most of the energy
is transferred by alternating electro-magnetic field

The fate of the alternating field

1. Dissipation in the wind: very difficult, extreme assumption (Lyubarsky&Kirk 2001; Kirk&Skjaeraasen 2003)

2. Dissipation at the termination shock: driven reconnection (Lyubarsky, in progress)

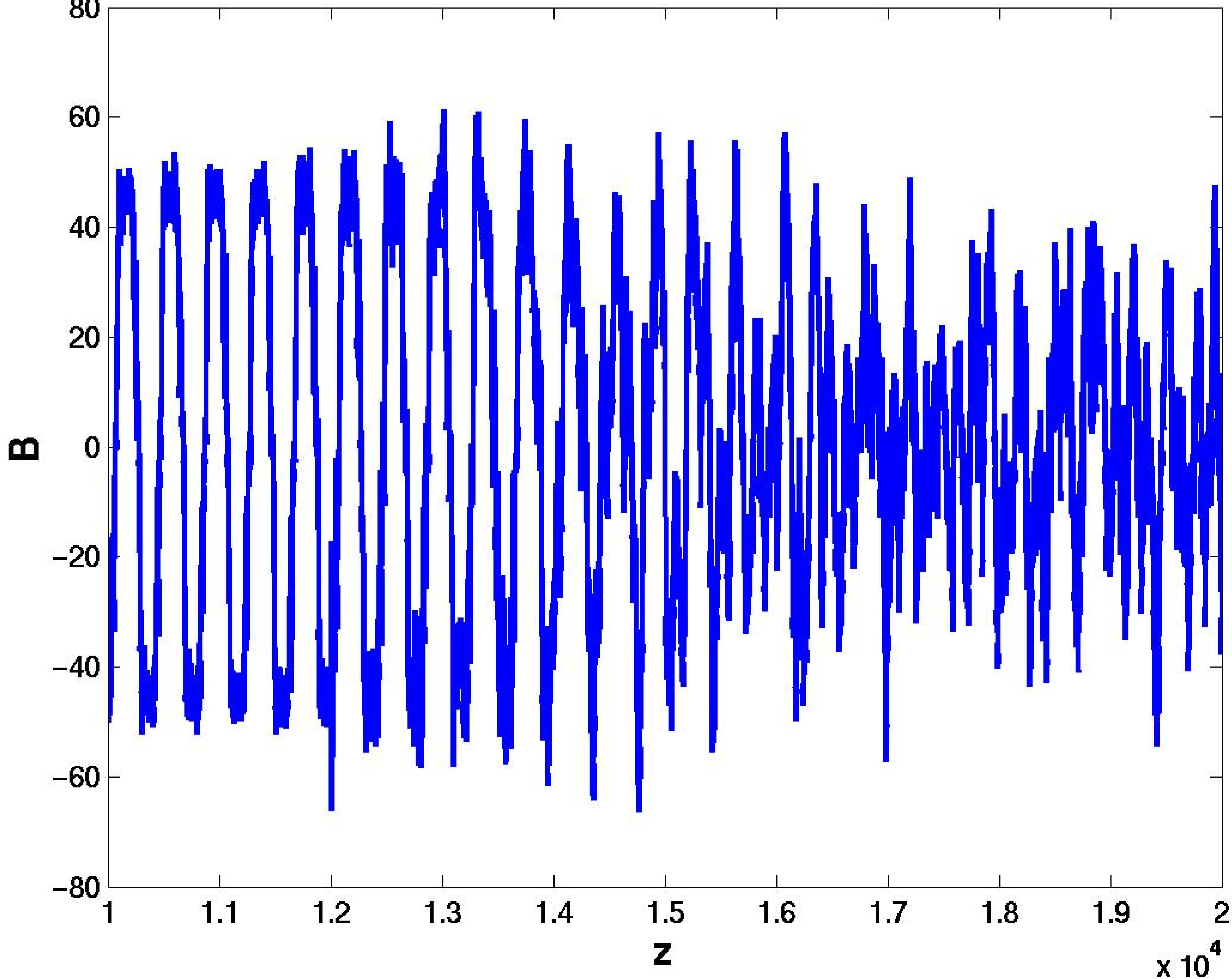
The shock in a striped wind (1.5D PIC simulations)



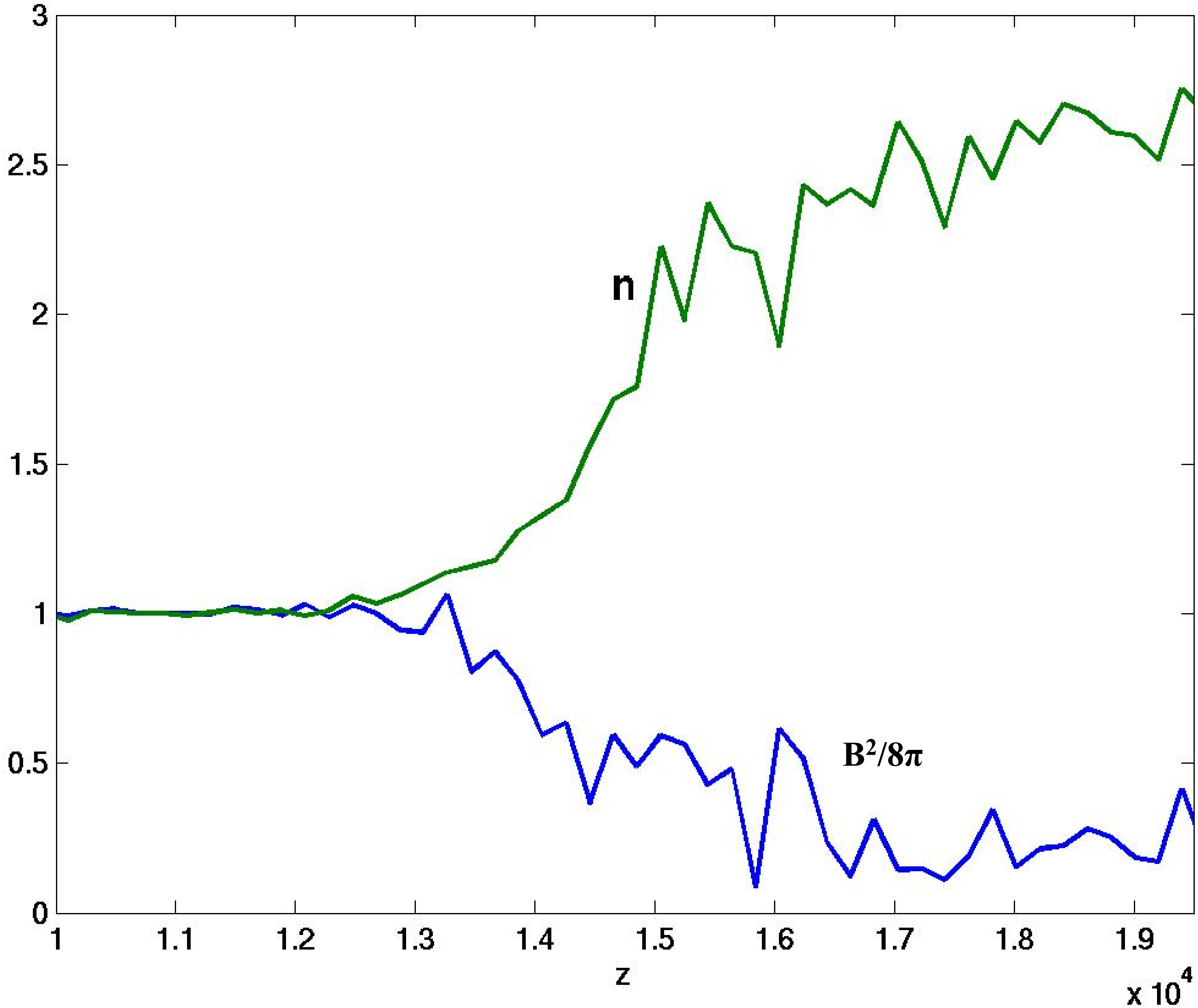
$\gamma = 7$

$\sigma = 2.5$

$N = 2 \times 400{,}000$



80
60
40
20
0
−20
−40
−60
−80
B
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
z
x 10^4

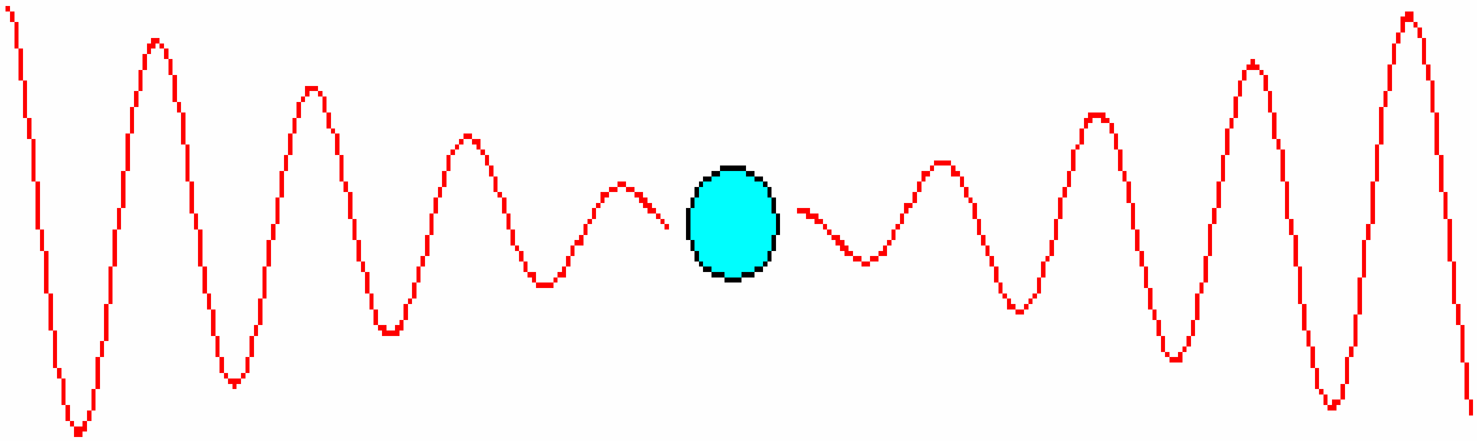


3
2.5
2
1.5
1
0.5
0
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
z
x 10^4
n
B^2/8π

MHD flow beyond the termination shock

is determined only by the total energy flux

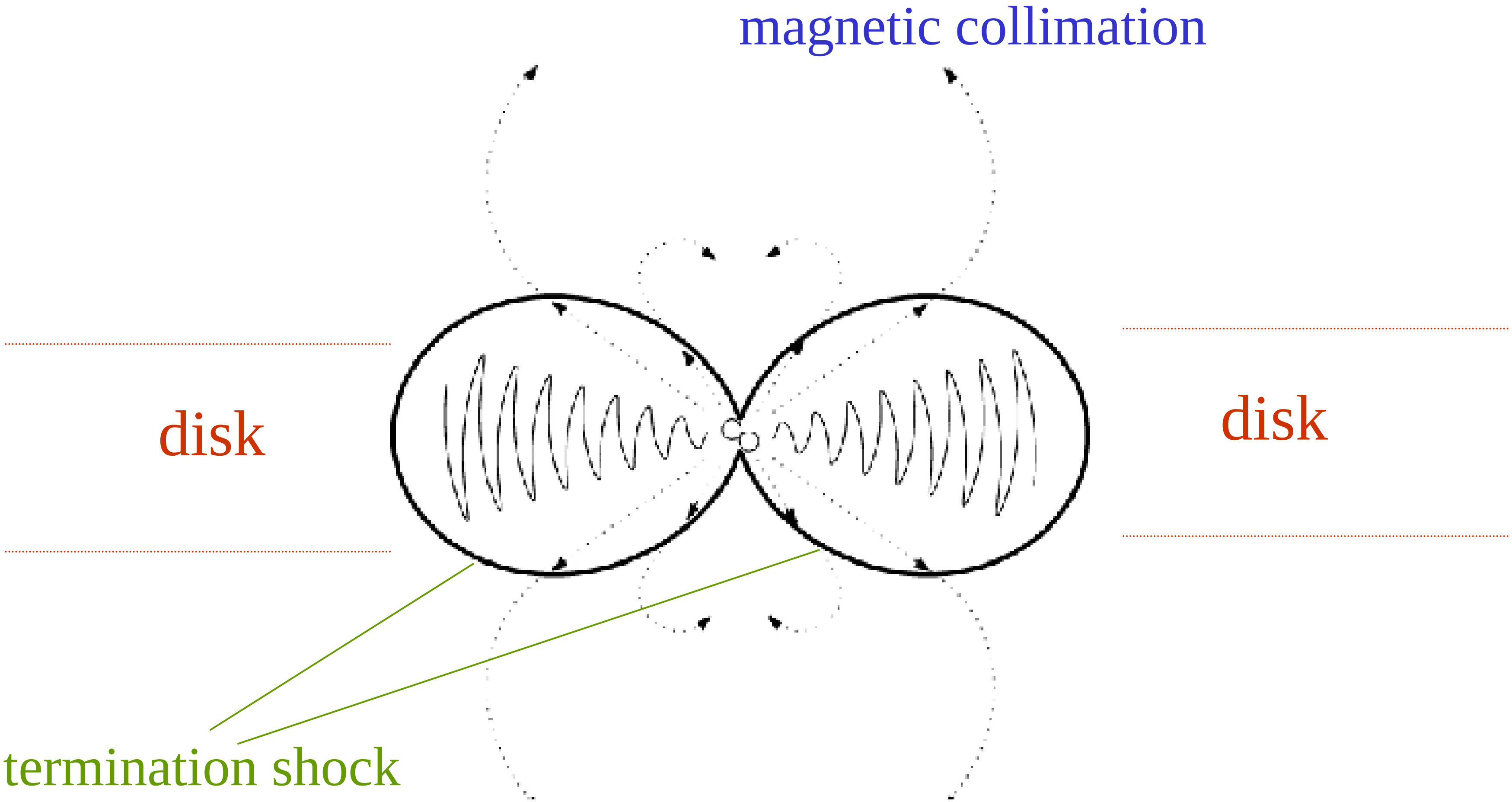
and the mean magnetic field in the wind



The mean field=0 at the equator

and at the axis

Origin of the get-torus structure (Lyubarsky 2002)



MHD simulations of the pulsar wind nebula

Komissarov & Lyubarsky 2003

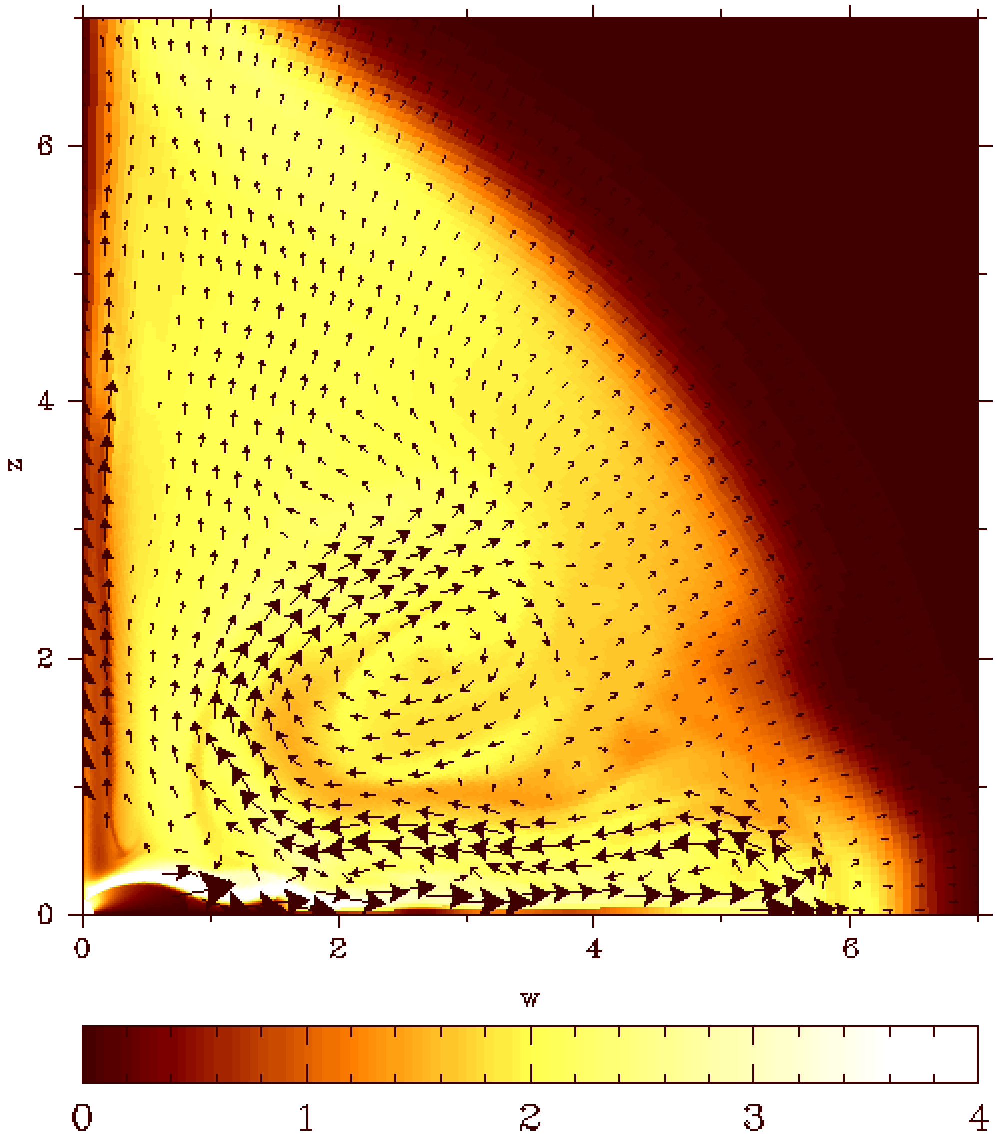
$$f_w = \frac{f_0}{r^2}(\sin^2\theta + 1/\sigma_0);$$

$$B = \sqrt{\frac{4\pi f_0}{c}}\frac{\xi}{r}\sin\theta\left(1 - \frac{2\theta}{\pi}\right); \qquad \xi \le 1$$

$$\sigma = 0.1\xi^2$$

Pulsar plasma fills in the cavity within the expanded cold envelope

magnetic field and velocity

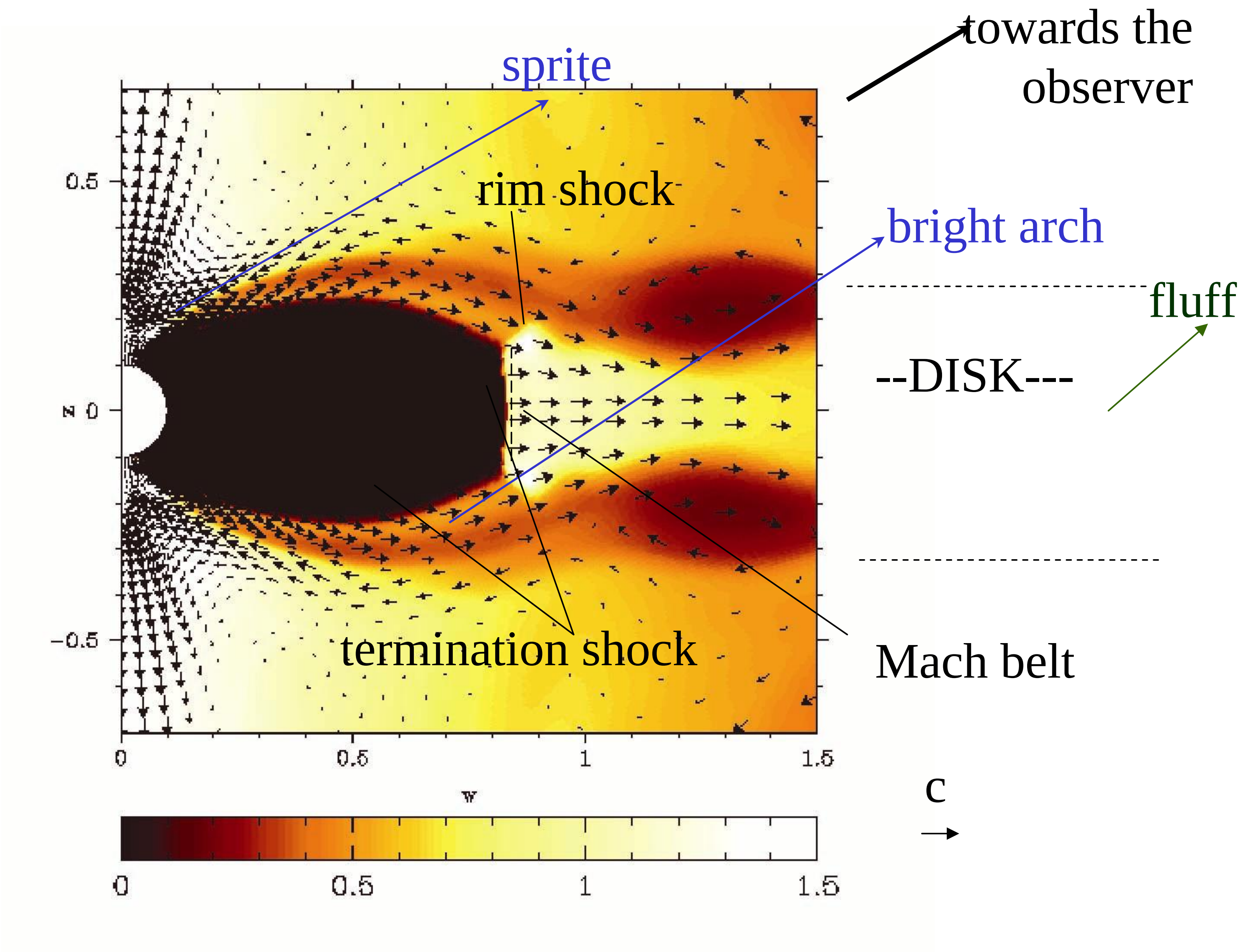


expansion velocity
5000 km/s

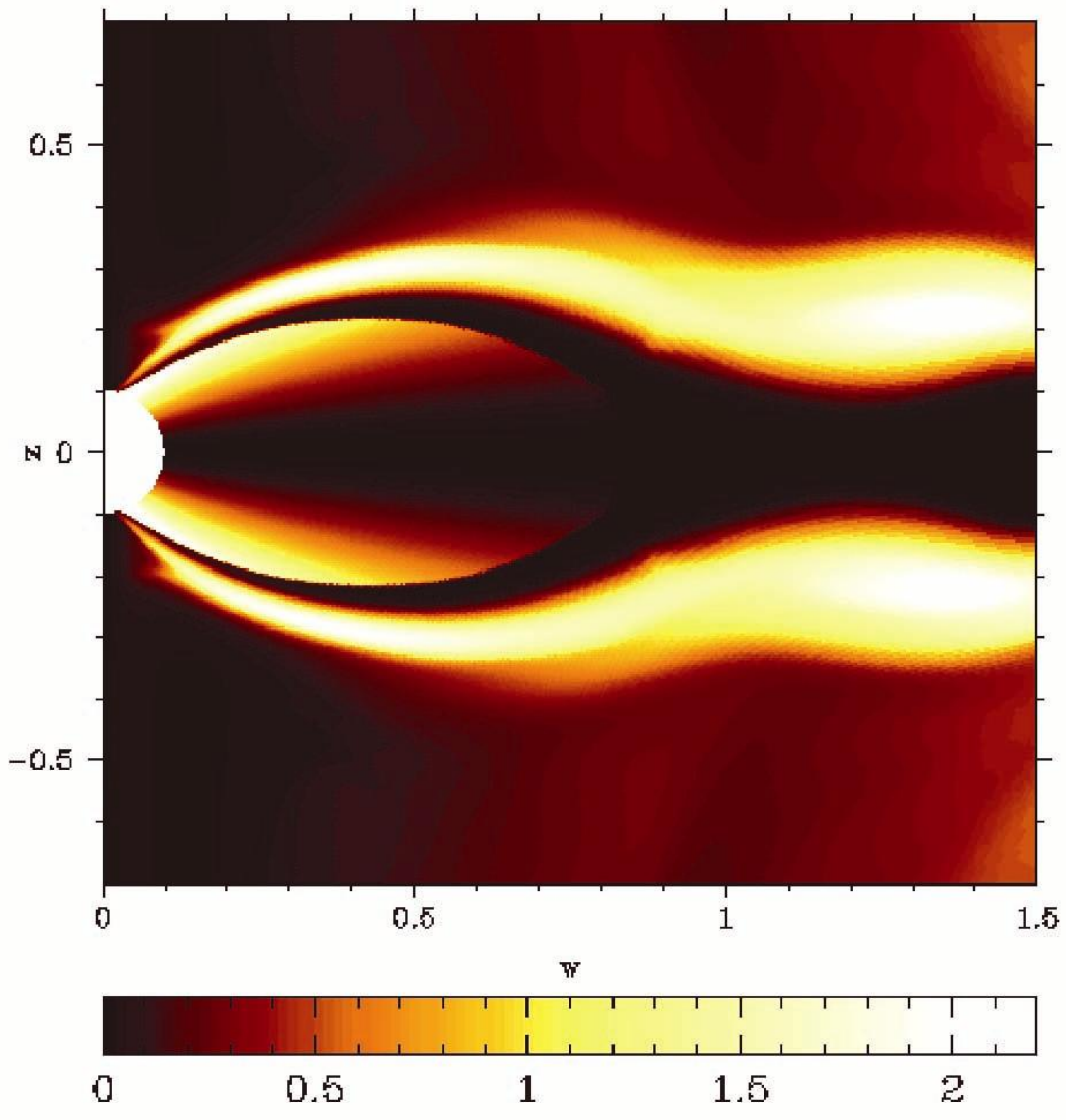
$\xi = 0.3$

$\sigma = 0.009$

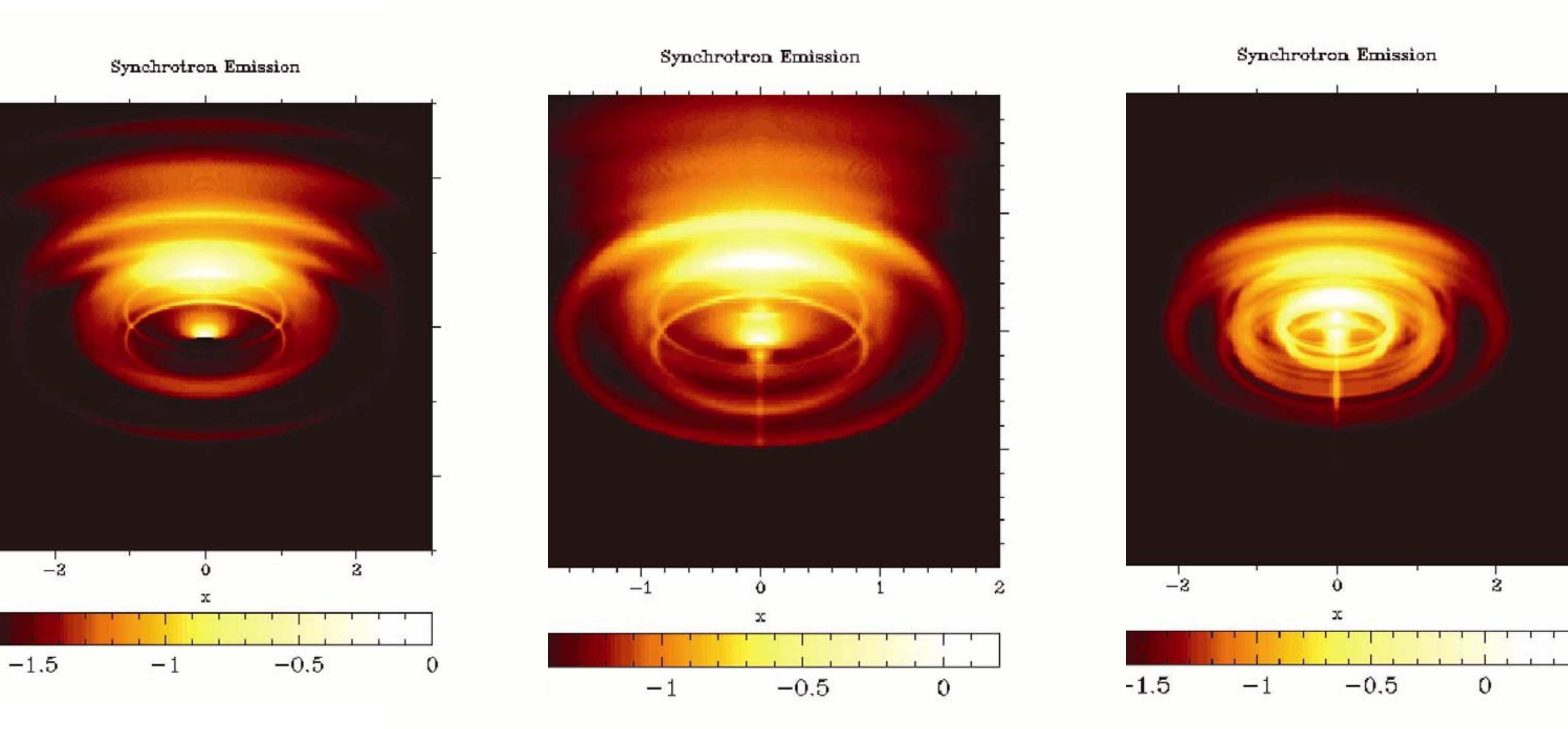
Gas pressure and velocity field around the termination shock



Magnetic pressure/gas pressure

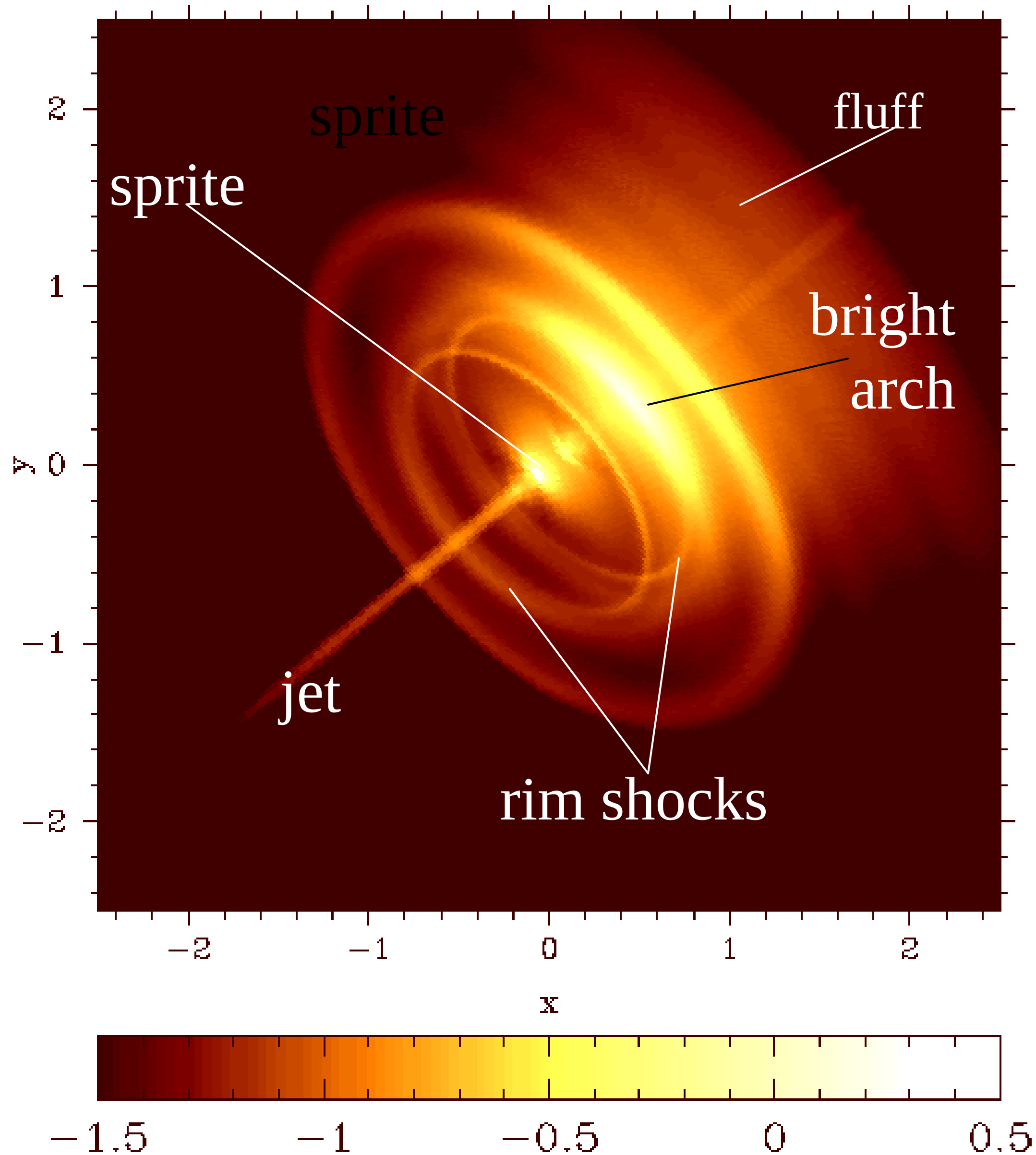


Simulated images

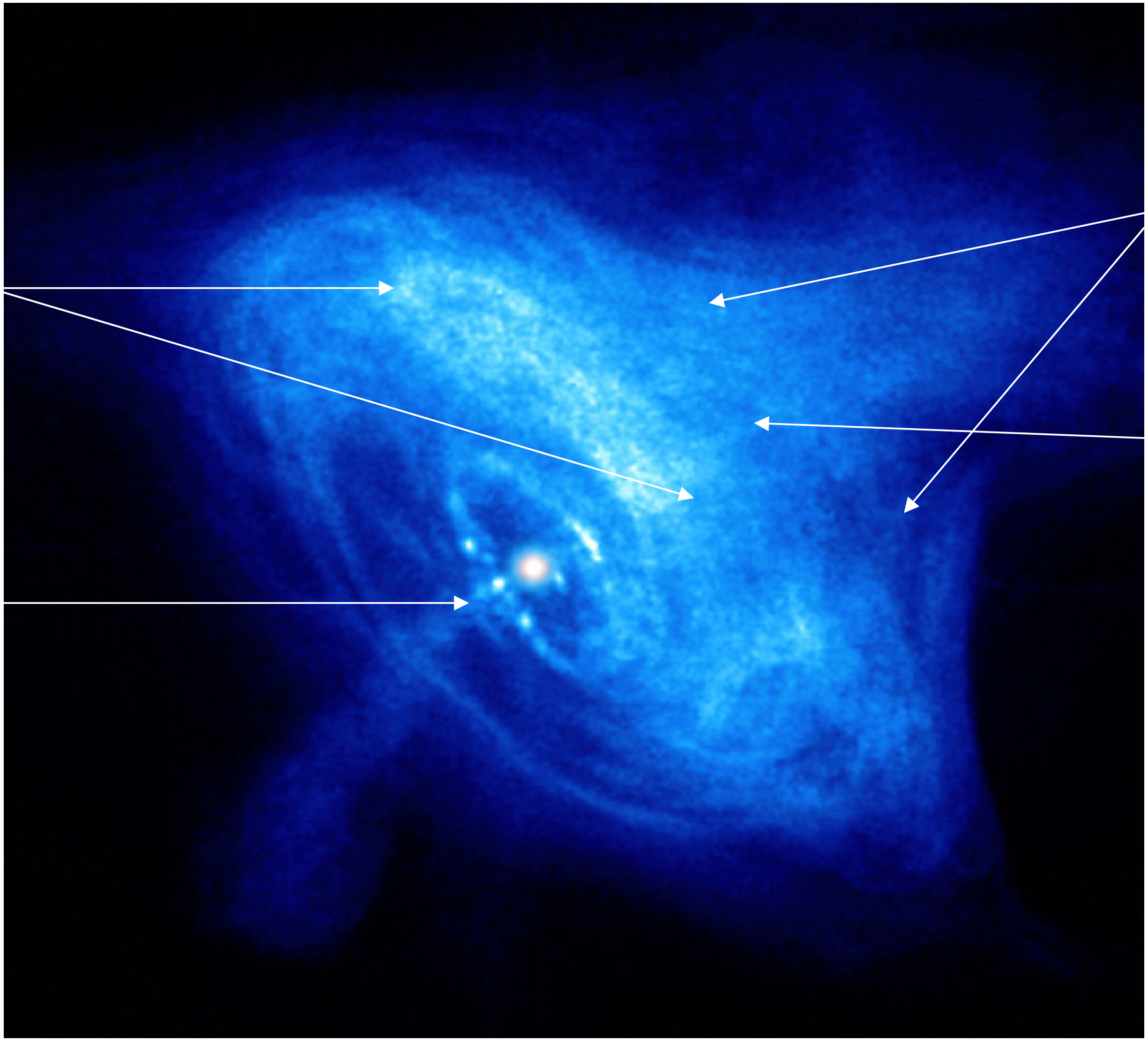


σ=0.004 σ=0.009 σ=0.025

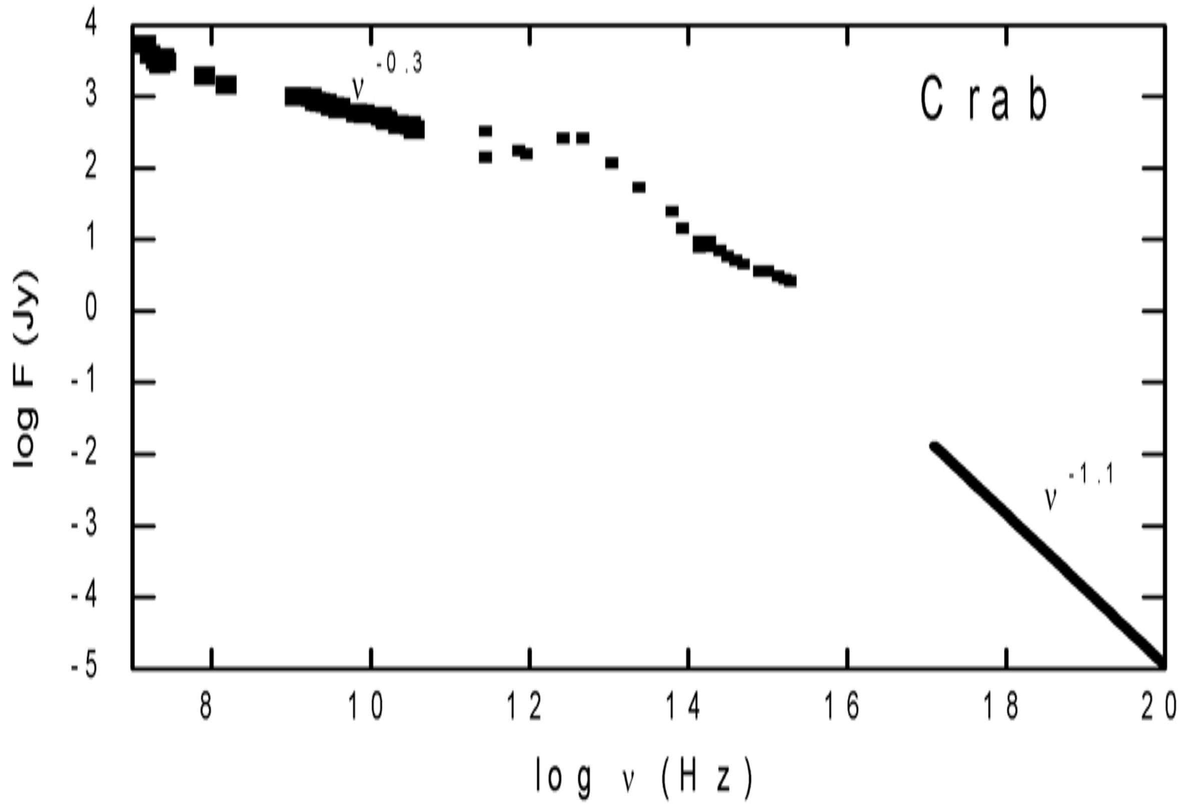
Simulated image, σ=0.009, *with magnetic field at the axis*

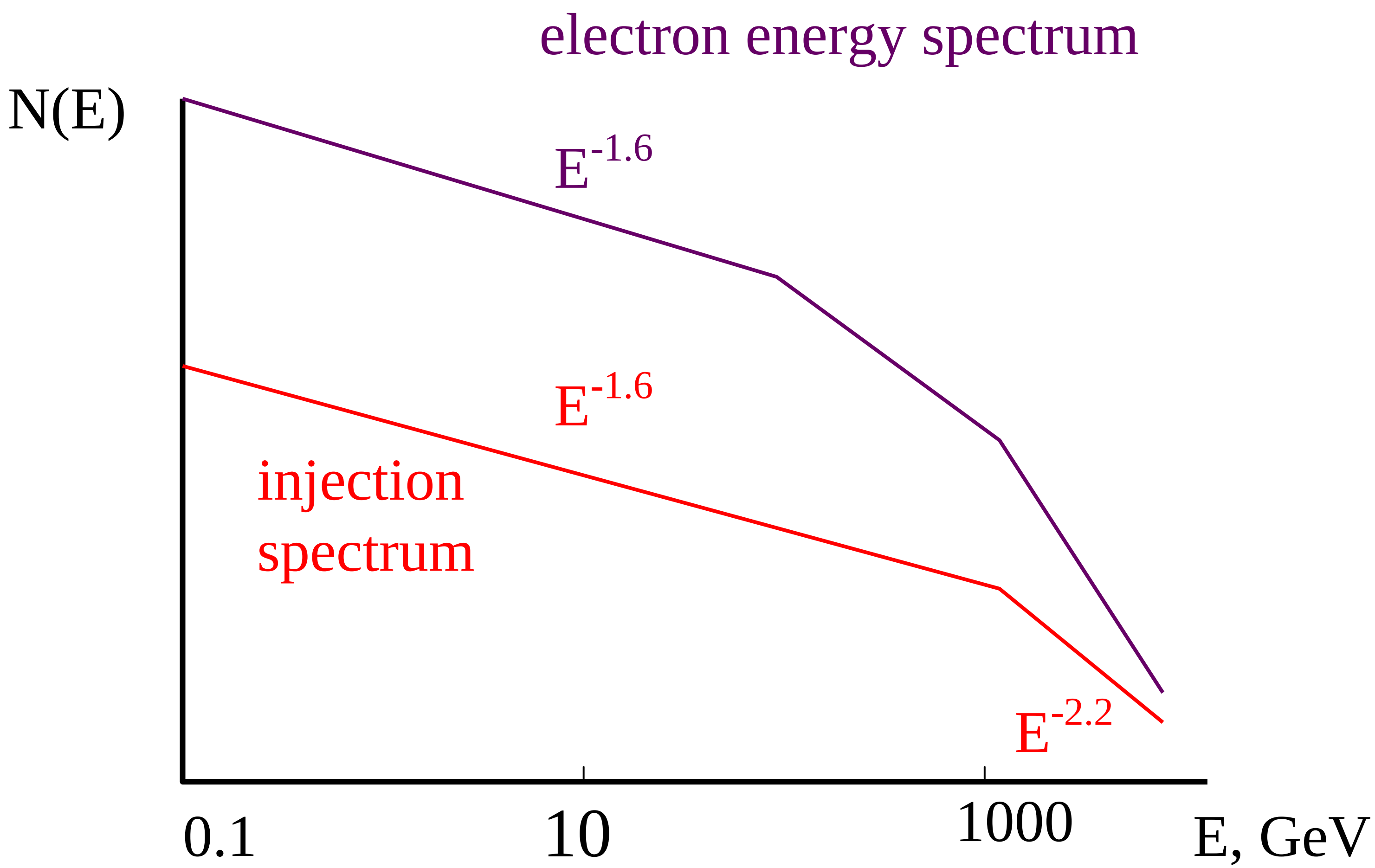


Chandra image of the Crab Nebula

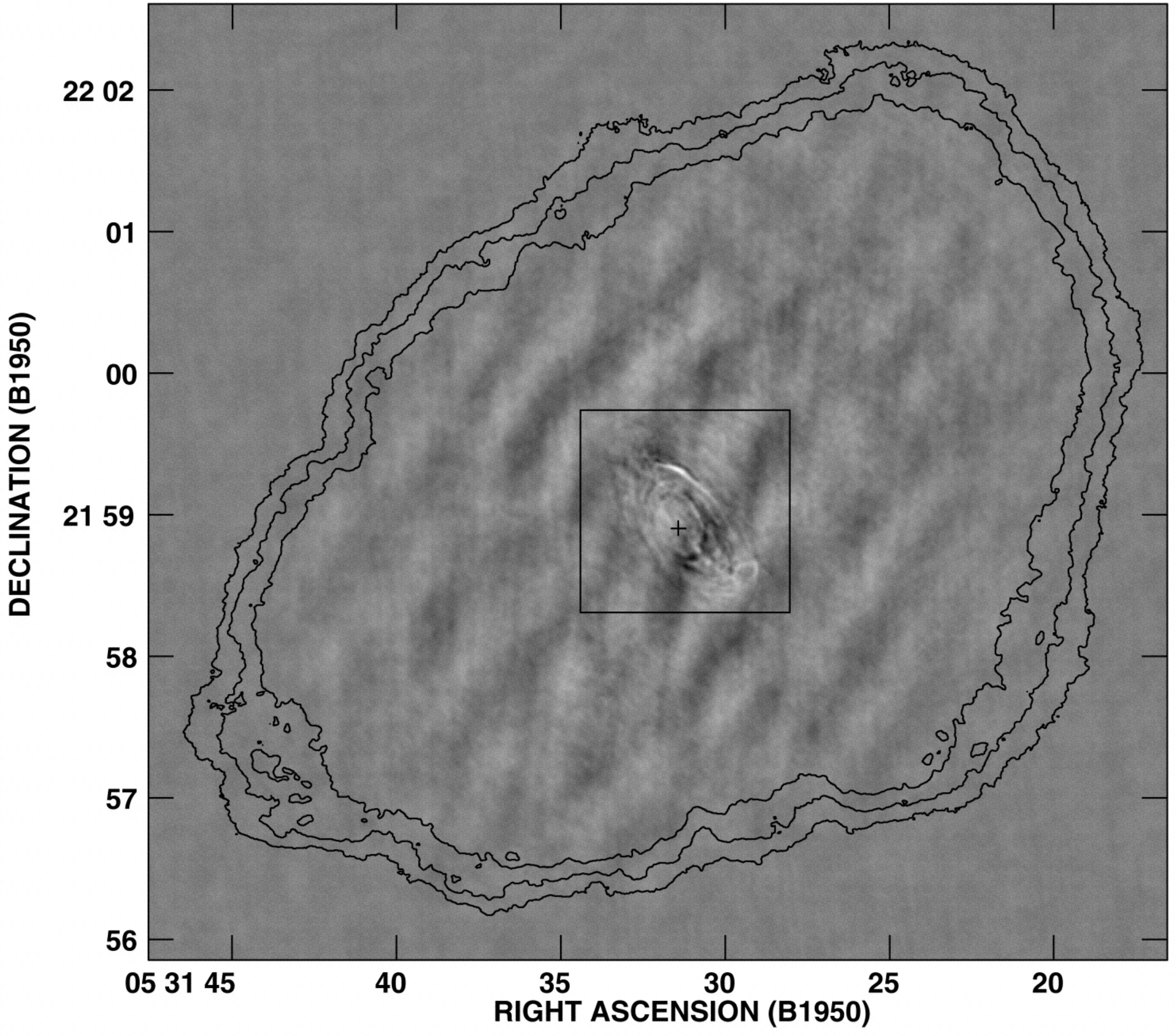


Particle acceleration at the termination shock in a striped wind





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)

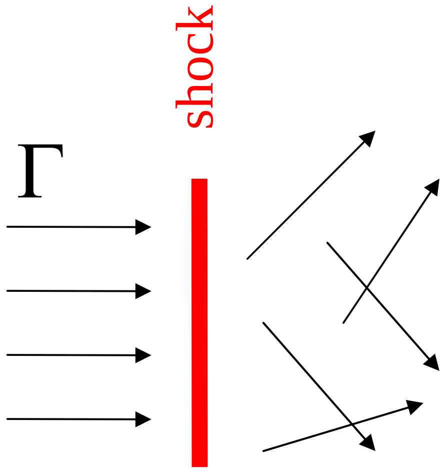


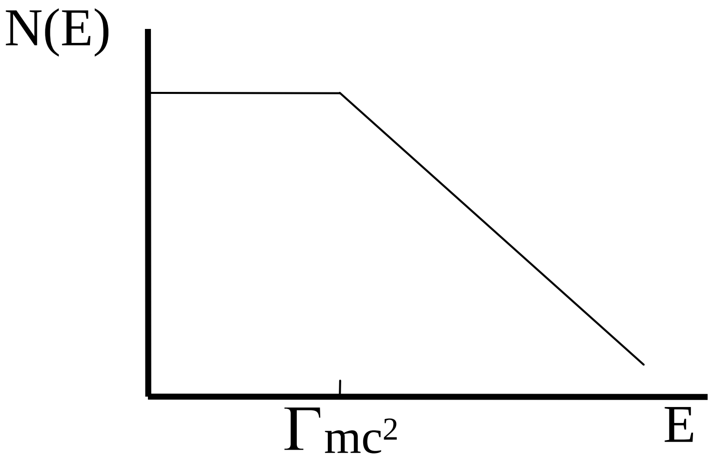
Difference image at 4615 MHz (1998 Aug 9-Oct 13)

$$N(E) = KE^{-1.6} \quad \text{from} \quad E_{\min} \leq 100\,\text{MeV} \quad \text{to} \quad E_{br} \approx 1\ \text{TeV}$$

$$N = \int N(E)dE = \tfrac{K}{0.6}E_{\min}^{-0.6} \qquad \varepsilon = \int EN(E)dE = \tfrac{K}{0.4}E_{br}^{0.4}$$

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)

1. Gallant, van der Swalluw, Kirk, Achterberg (2002):

Ion dominated wind

$$\Gamma \approx 100; \qquad \dot{N}_p \approx 10^{39}\ \mathrm{s}^{-1}; \qquad \dot{N}_{e^\pm} \approx 10^{40} \div 10^{41}\ \mathrm{s}^{-1}$$

$$\dot{N}_{GJ} = 3 \cdot 10^{34}\ \mathrm{s}^{-1}$$

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

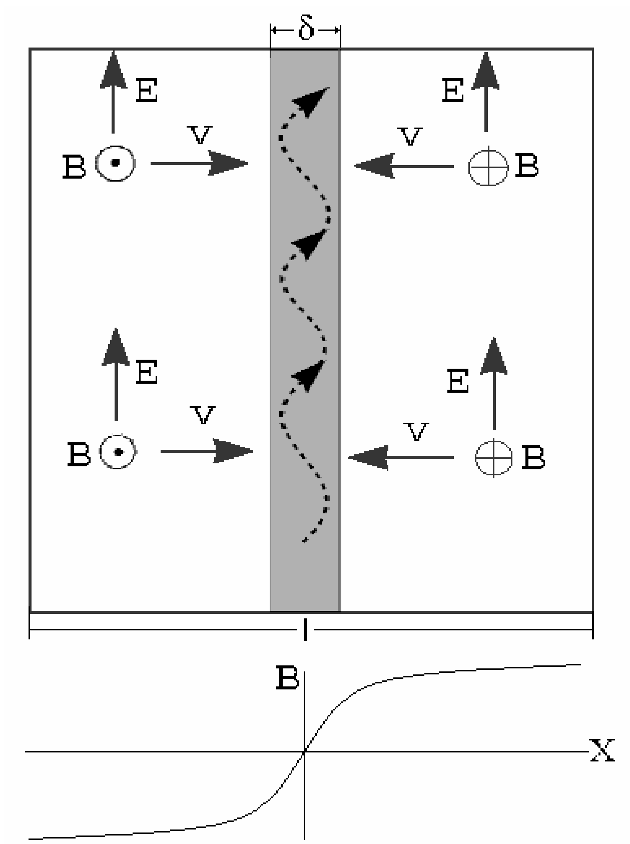
4. The jet is formed beyond the termination shock

Unsolved problems

1. Azimuthal symmetry of the internal ring.

2. Wisps

3. Flat spectrum of the radio emitting electrons

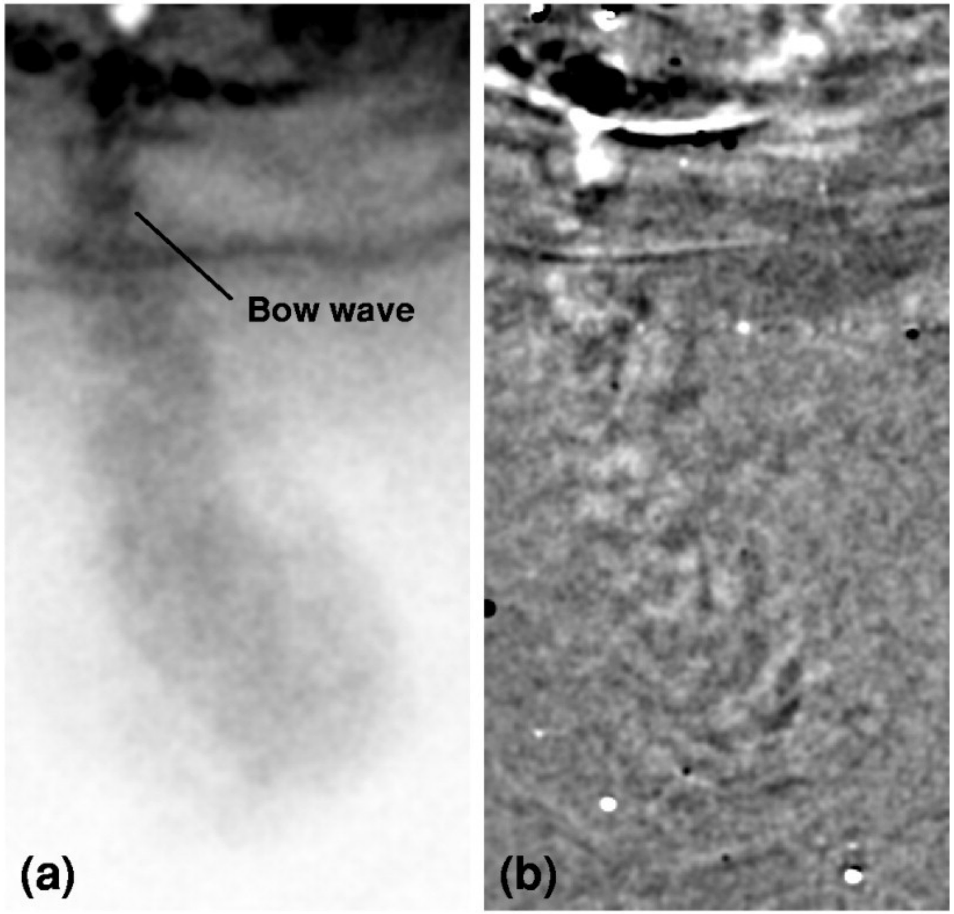


$$r_L = \frac{\varepsilon}{eB}$$

$$\delta \approx \sqrt{\frac{\varepsilon_{\max}}{eB_0}}$$

$$E = \frac{v}{c} B \propto \varepsilon$$

Crab's jet



Chandra

HST
difference image