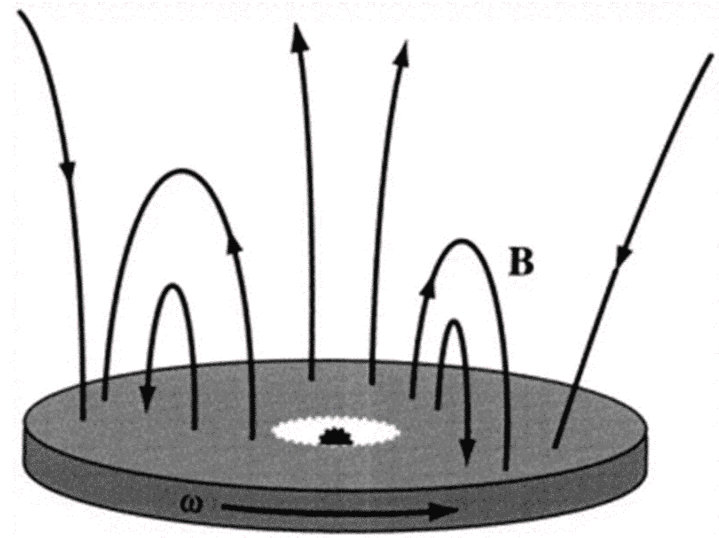
Explosive Formation of Poynting Jets

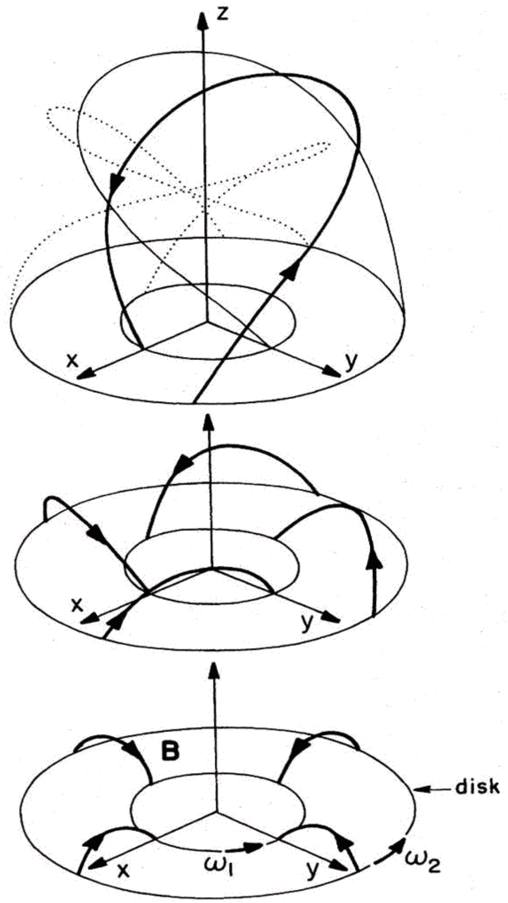
R. Lovelace and M. Romanova,
Cornell University

Accretion Disk with Loops



Romanova, Ustyugova, Koldoba, Chechetkin, Lovelace 1998

Inflation of the field lines:

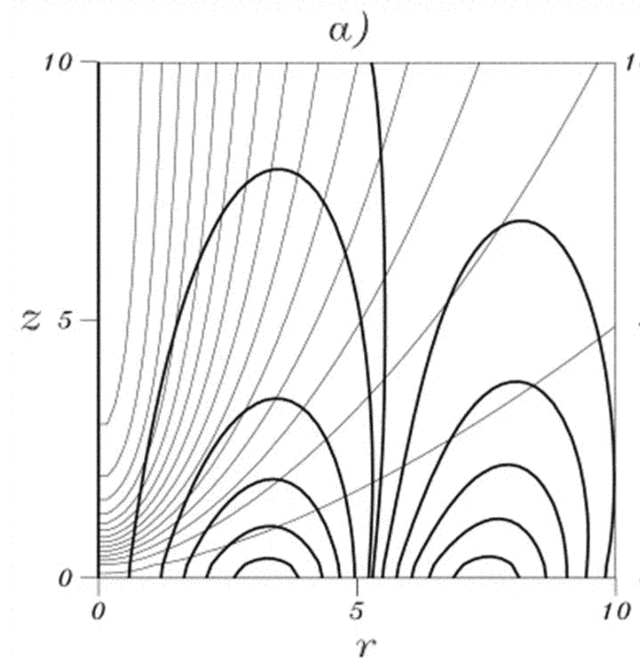


Magnetic field lines, connecting different parts of the disk, inflate as a result of difference in angular velocities of the foot-points

Aly (1985); Newman, Newman & Lovelace (1992); Lovelace, Romanova & Bisnovatyi-Kogan (1995)

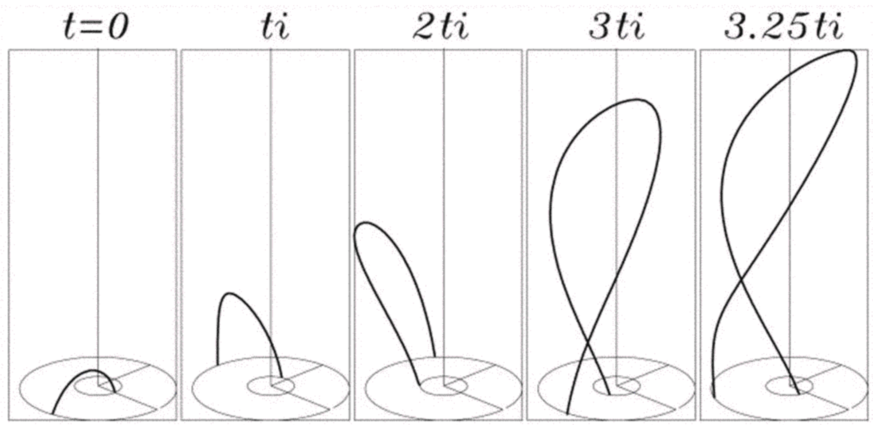
2D axisymmetric Modeling of Loops

Initial Configuration: two loops



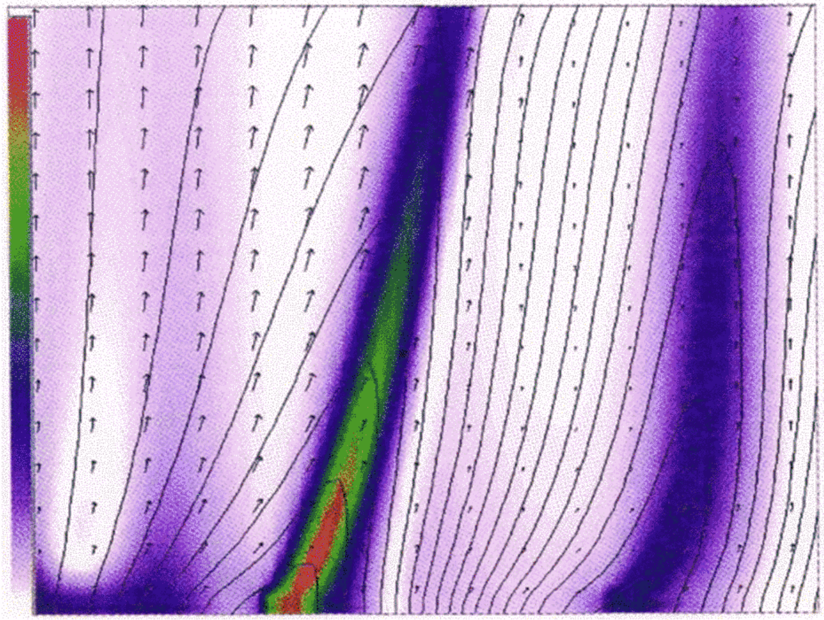
Romanova, Ustyugova, Koldoba, Chechetkin, Lovelace 1998

Loops Inflate



Romanova, Ustyugova, Koldoba, Chechetkin, Lovelace 1998

Final Configuration:



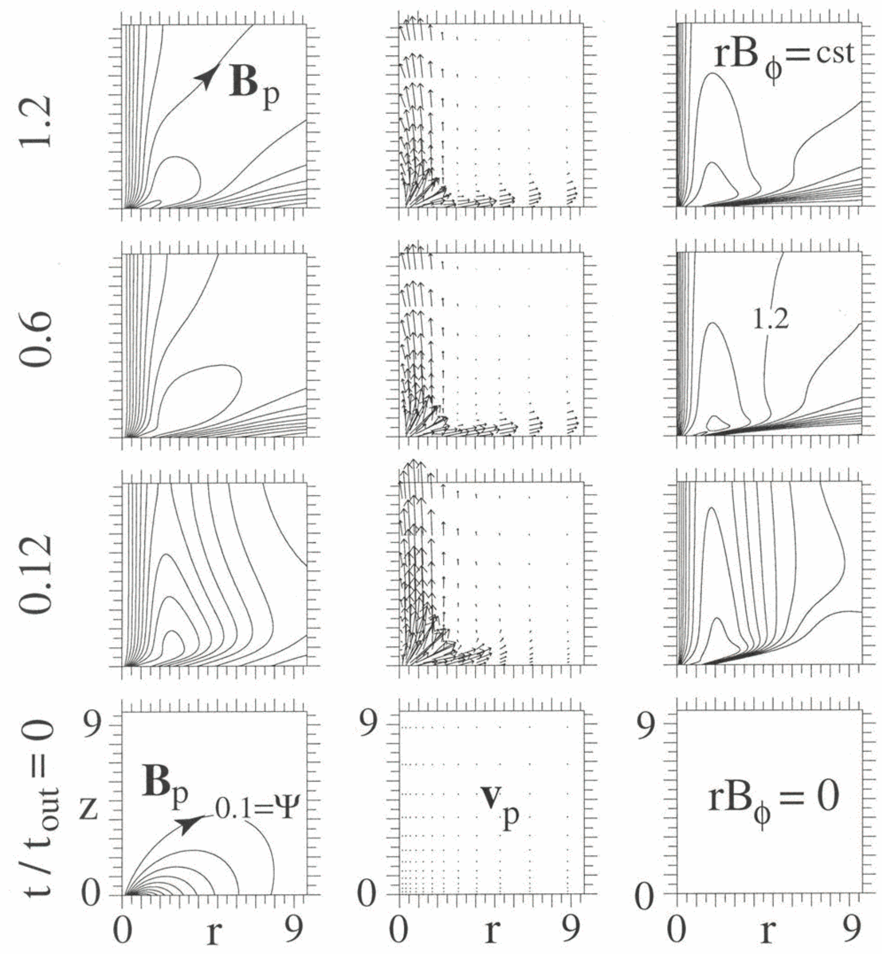
Background: current

Energy outflow: Poynting flux

Romanova, Ustyugova, Koldoba, Chechetkin, Lovelace 1998

MHD Simulations (non-relativistic)

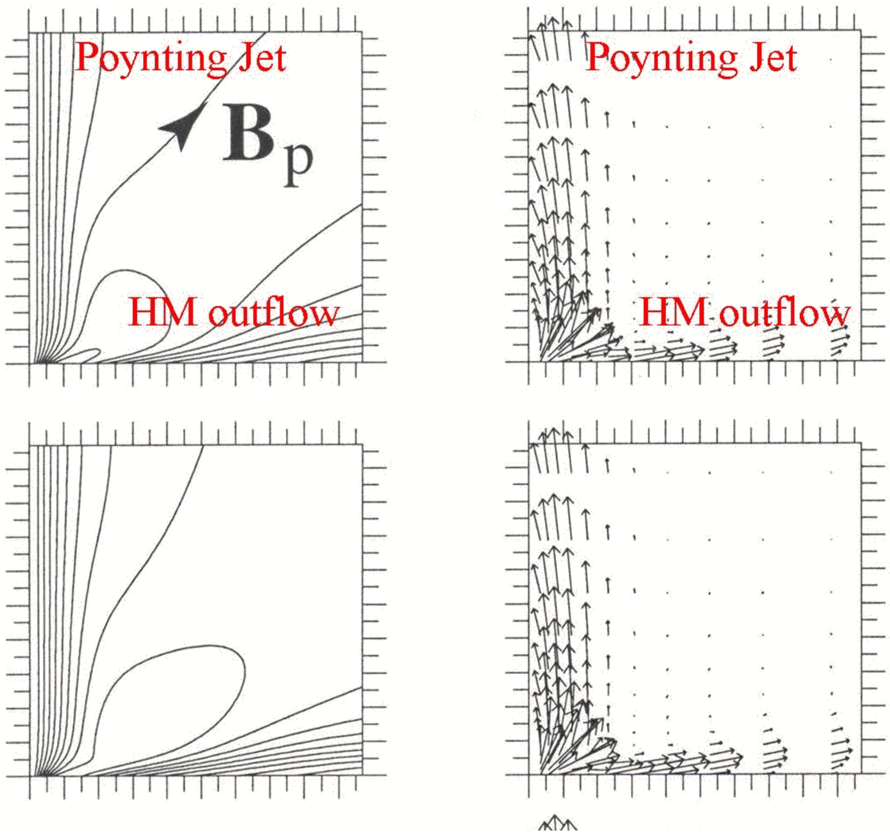
Non-Relativistic Poynting Jets



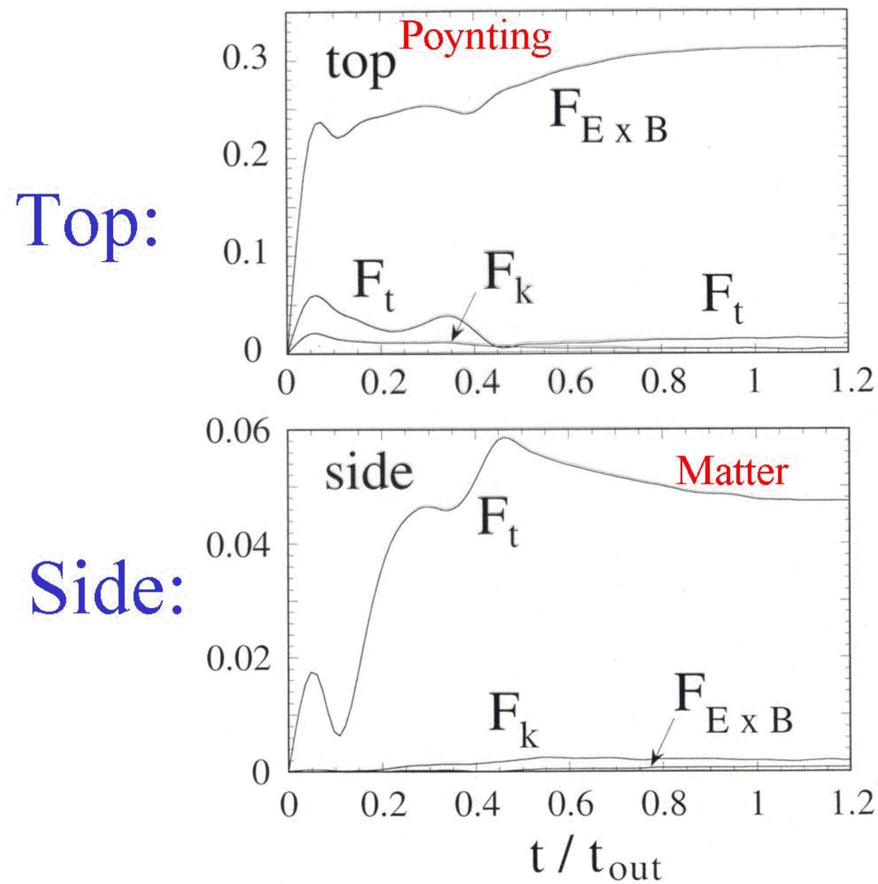
Ustyugova, Lovelace, Romanova, Li, Colgate 2000,

Two Types of Flow:

- Poynting flux jet along the z-axis
- Hydromagnetic outflow, r-direction

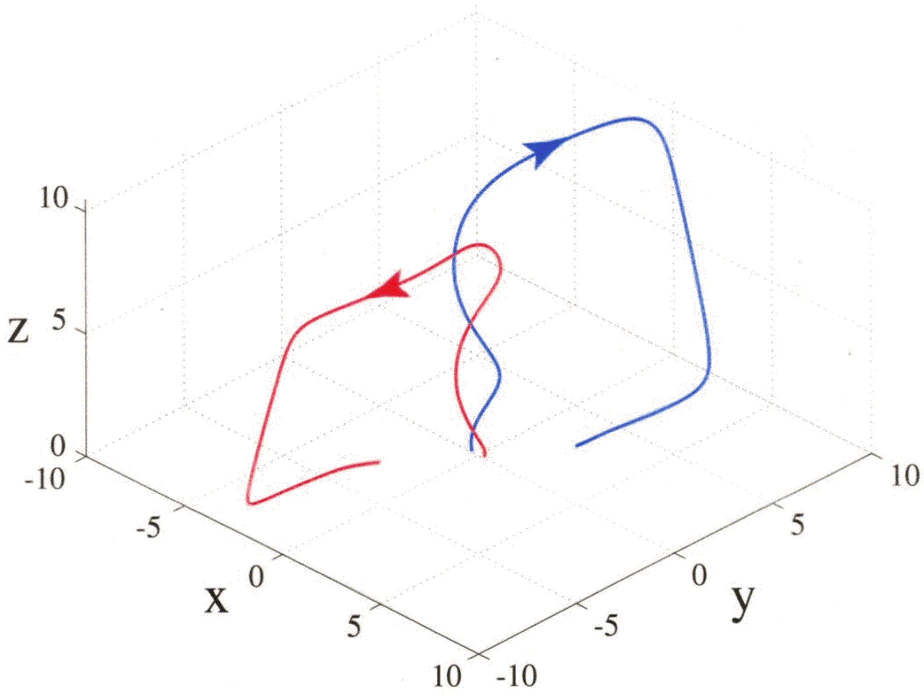


Fluxes through the boundaries



Three dimensional view of two field lines

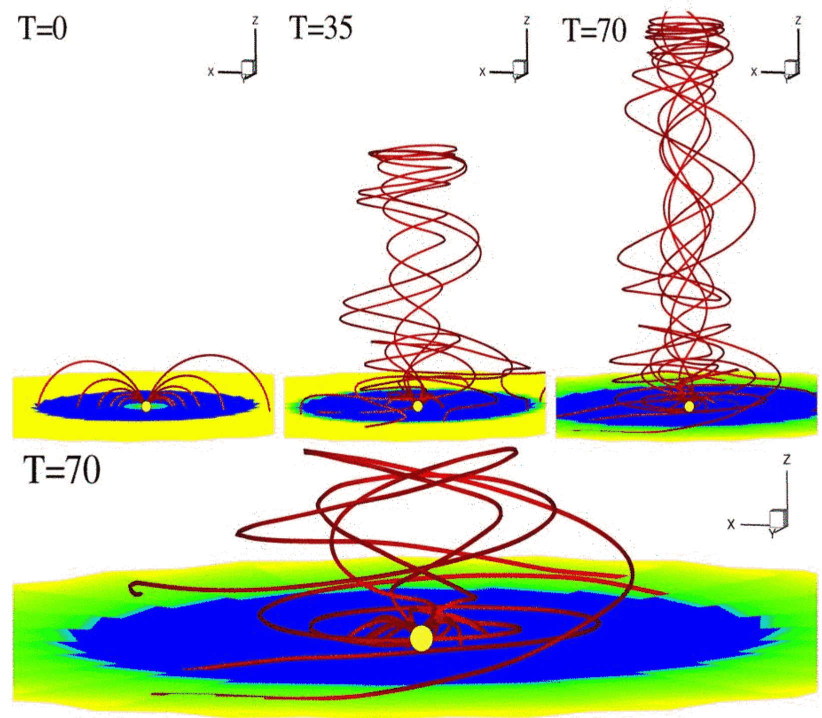
Grad-Shafranov Equation



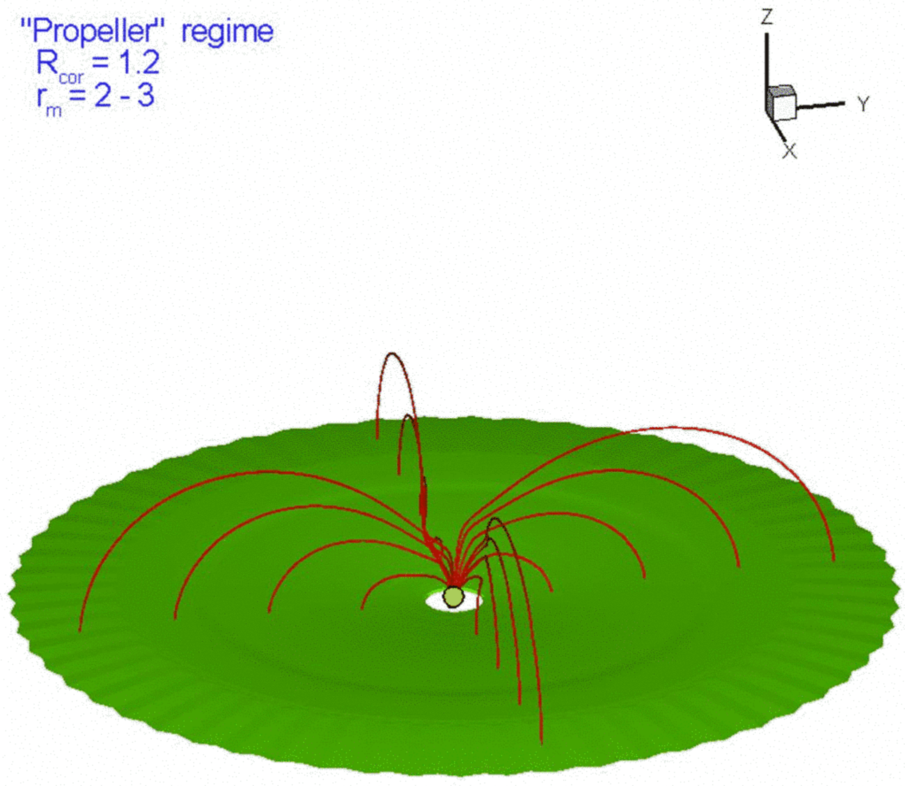
Lovelace, Li, Koldoba, Ustyugova, Romanova 2002

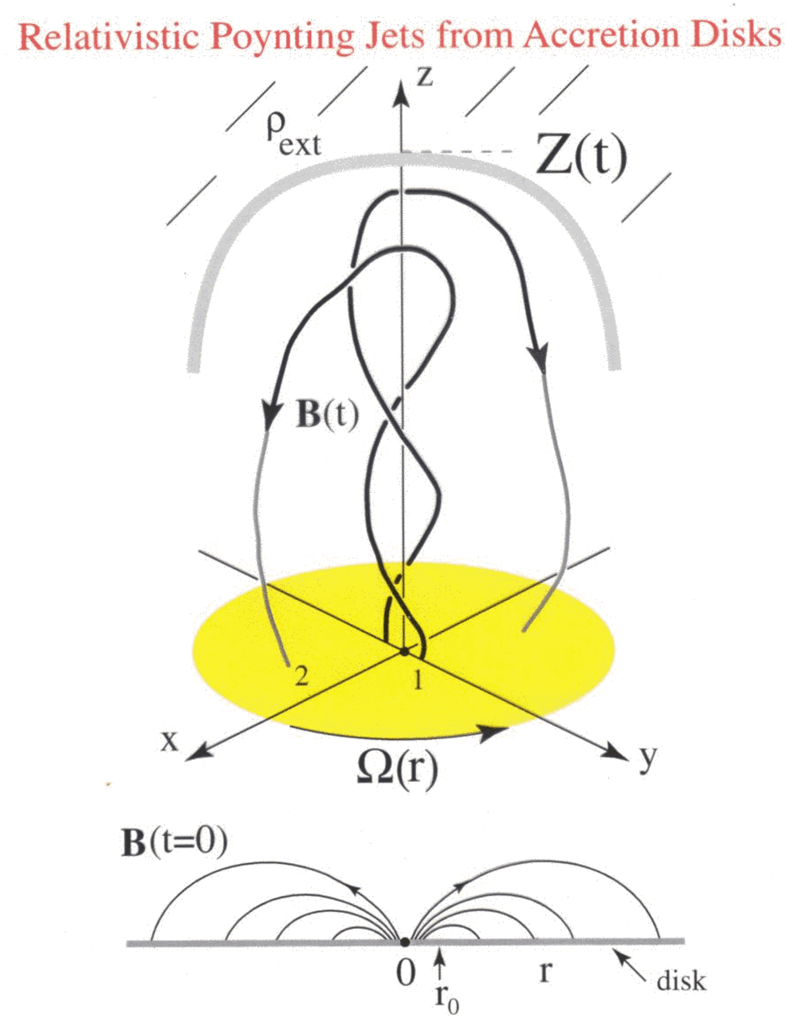
Magnetic field lines expand up, forming a magnetic "tower"

2D MHD Simulations



Kato et al. 2004, Romanova et al. 2004


"Propeller" regime
$R_{cor} = 1.2$
$r_m = 2 - 3$
Z
Y
X


Relativistic Poynting Jets from Accretion Disks
z
ρ_{ext}
Z(t)
B(t)
2
1
x
y
Ω(r)
B(t=0)
0
r_0
r
disk

Relativistic Poynting Jets from Accretion Disks

(Lovelace & Romanova, 2003 ApJ, 596, L59)

The "head" of the Poynting jet propagates outward with a velocity which may be relativistic. The Lorentz factor of the head is

$$\Gamma = [B_0^2/(8\pi\mathcal{R}^2\rho_{ext}c^2]^{1/6}$$

if this quantity is much larger than unity. For conditions pertinent to an active galactic nuclei,

$$\Gamma \approx 8(10/\mathcal{R})^{1/3}(B_0/10^3\mathrm{G})^{1/3}(1/\mathrm{cm}^3/n_{ext})^{1/6}$$

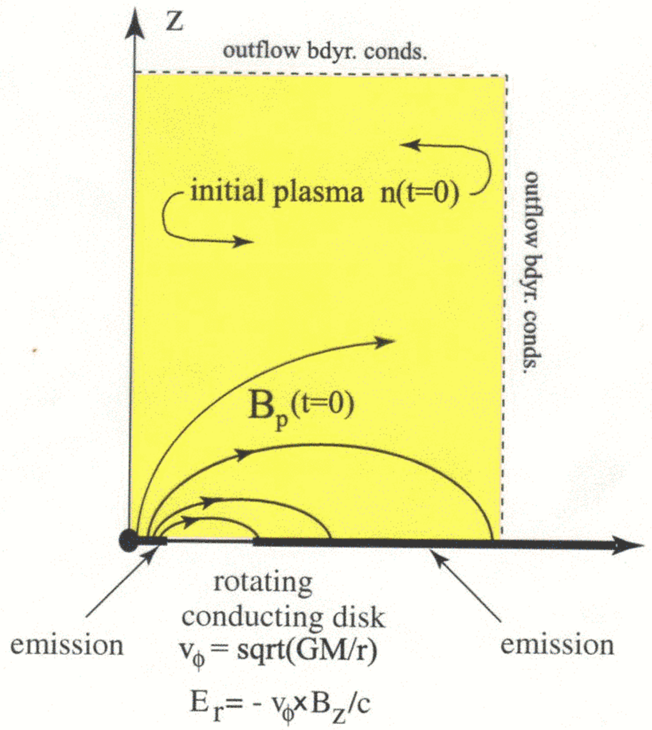
where B_0 is the magnetic field strength close to the black hole, $\rho_{ext} = \bar{m}n_{ext}$ is the mass density of the ambient medium into which the jet propagates, $\mathcal{R} = r_0/r_g > 1$, where $r_g \equiv GM/c^2$ is the gravitational radius of the black hole, and r_0 is the radius of the $O-$point of the initial dipole field. This model offers an explanation for the observed Lorentz factors $\sim$ 10 of parsec-scale radio jets measured with very long baseline interferometry.

Relativistic PIC Simulations

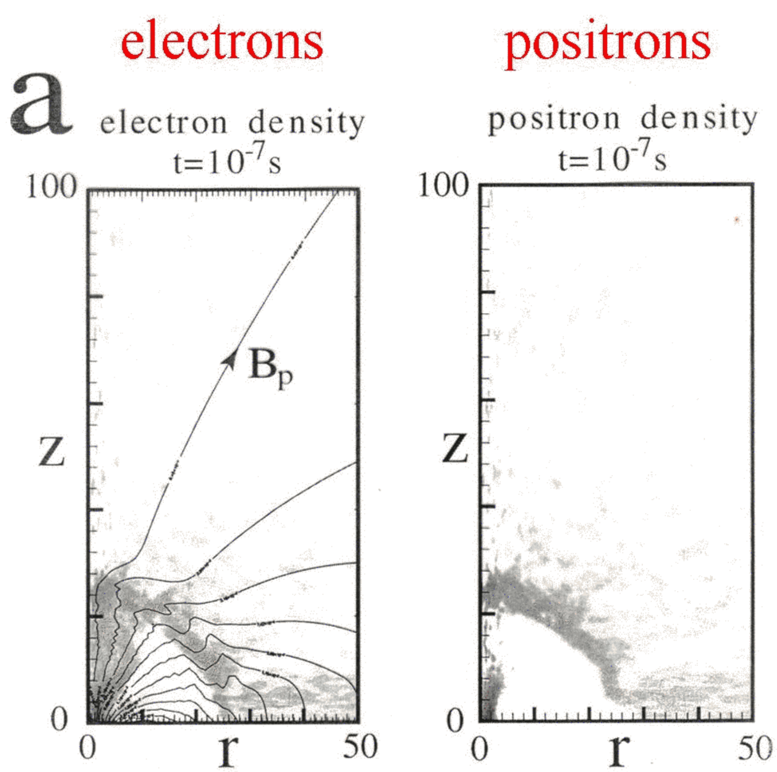
Relativistic, Fully Electromagnetic Particle in Cell Simulations of Jet Formation

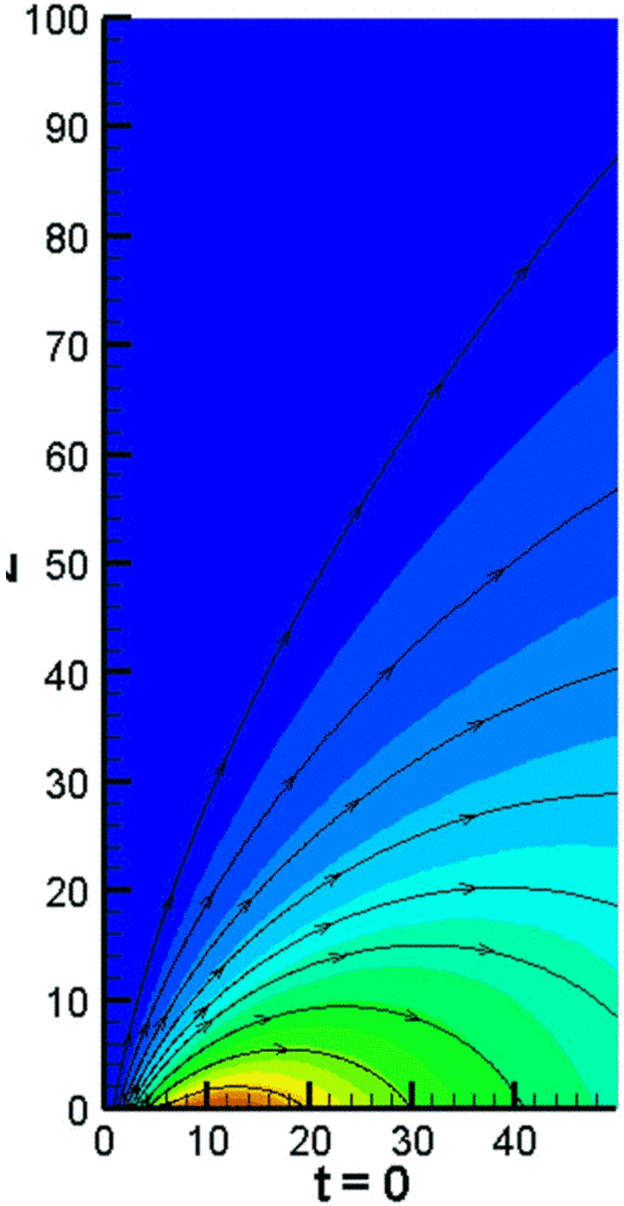
P. Gandhi, R. Lovelace, & M. Romanova

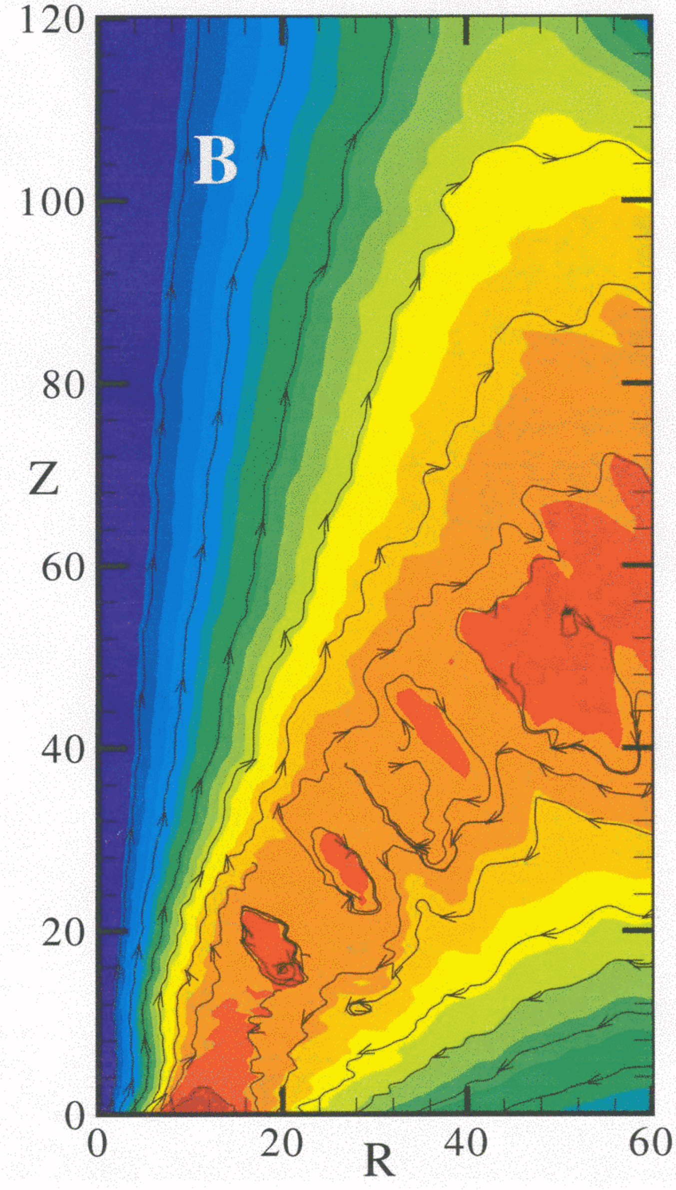
Code: XOOPIC See J.P. Verboncoeur, A.B. Langdon, and N.T. Gladd 1995, ``An Object-Oriented Electromagnetic PIC Code," Comp. Phys. Comm., 87, 199-211



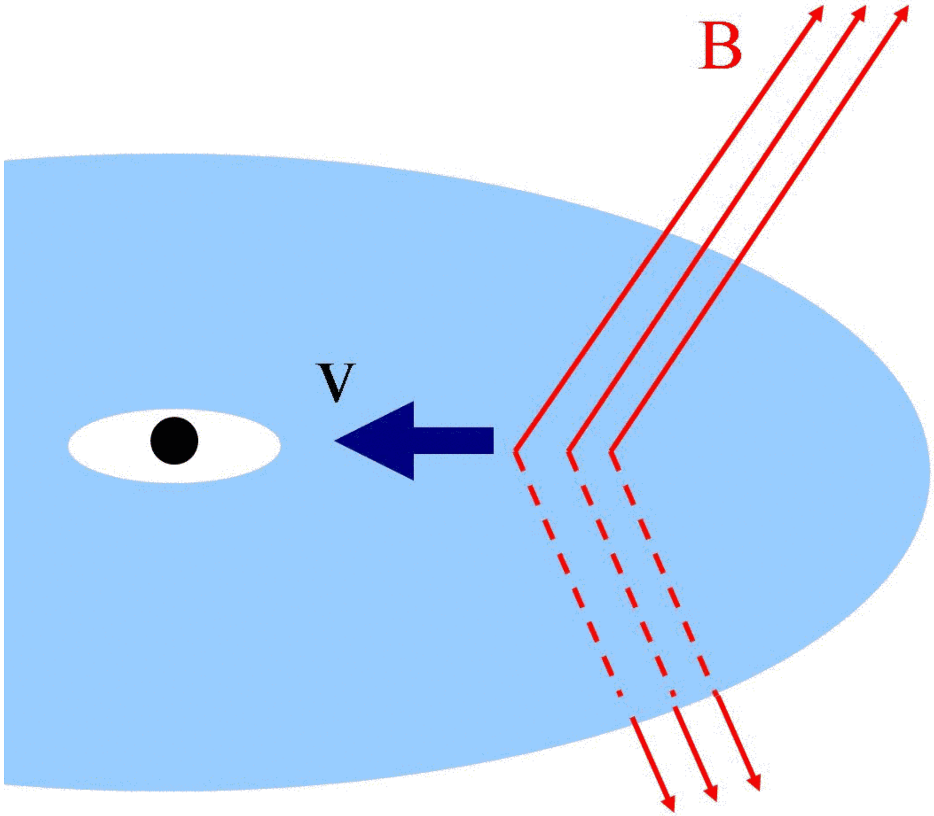
Injection of Leptons




100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
t = 0

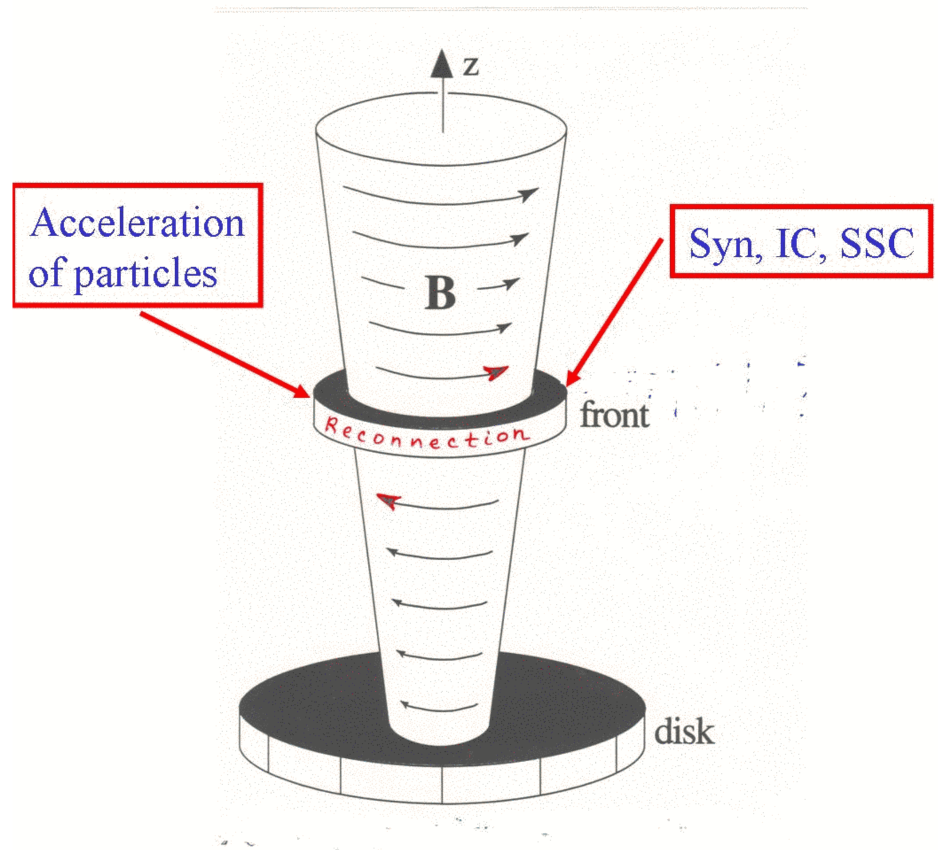

B
120
100
80
60
40
20
0
Z
0
20
40
60
R

Global Magnetic Instability



Lovelace, Romanova, Newman 1994;
Konigl , Livio, Matsumoto, Shibata, Kato, Koide

Injection to the Jet



Blandford, Begelman, Sikora, Levinson, Kirk

Romanova & Lovelace 1997

Explosive Accretion Due to Magnetic Jets
(Lovelace & Romanova, 2005)

Quasi-stationary Poynting jets from the two sides of the disk within r_0 give an energy outflow per unit radius of the disk

$$d\dot{E}_B/dr = rv_K(-B_\phi B_z)_h \approx v_K(r_0)(\Psi_0/r_0)^2 \ ,$$

The h subscript indicates evaluation at the top surface of the disk, Ψ_0 is the polodial flux through the disk interior to the O-point at r_0. We find

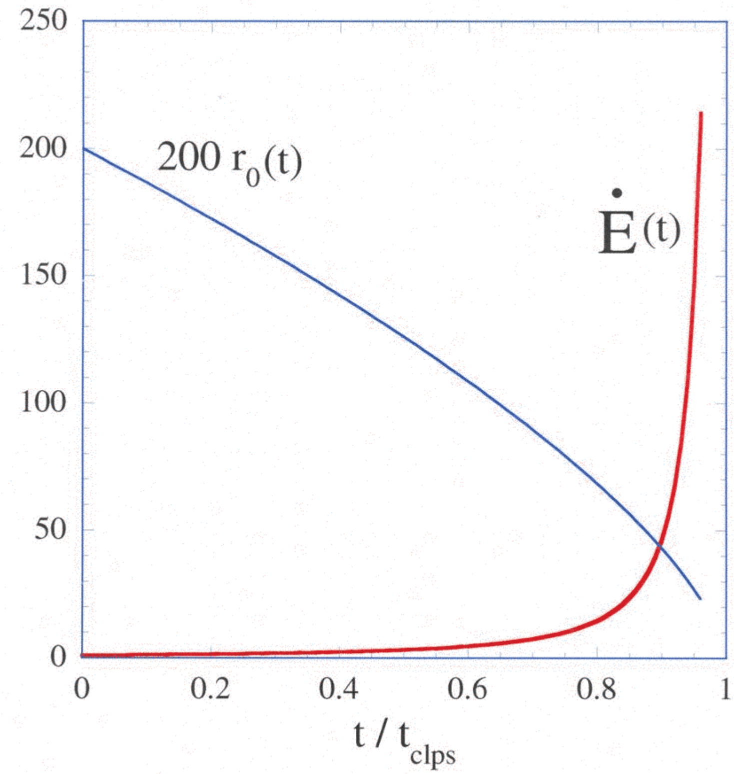
$$M_d \frac{dr_0}{dt} \approx \frac{-2\Psi_0^2}{\sqrt{GMr_0(t)}} \ ,$$

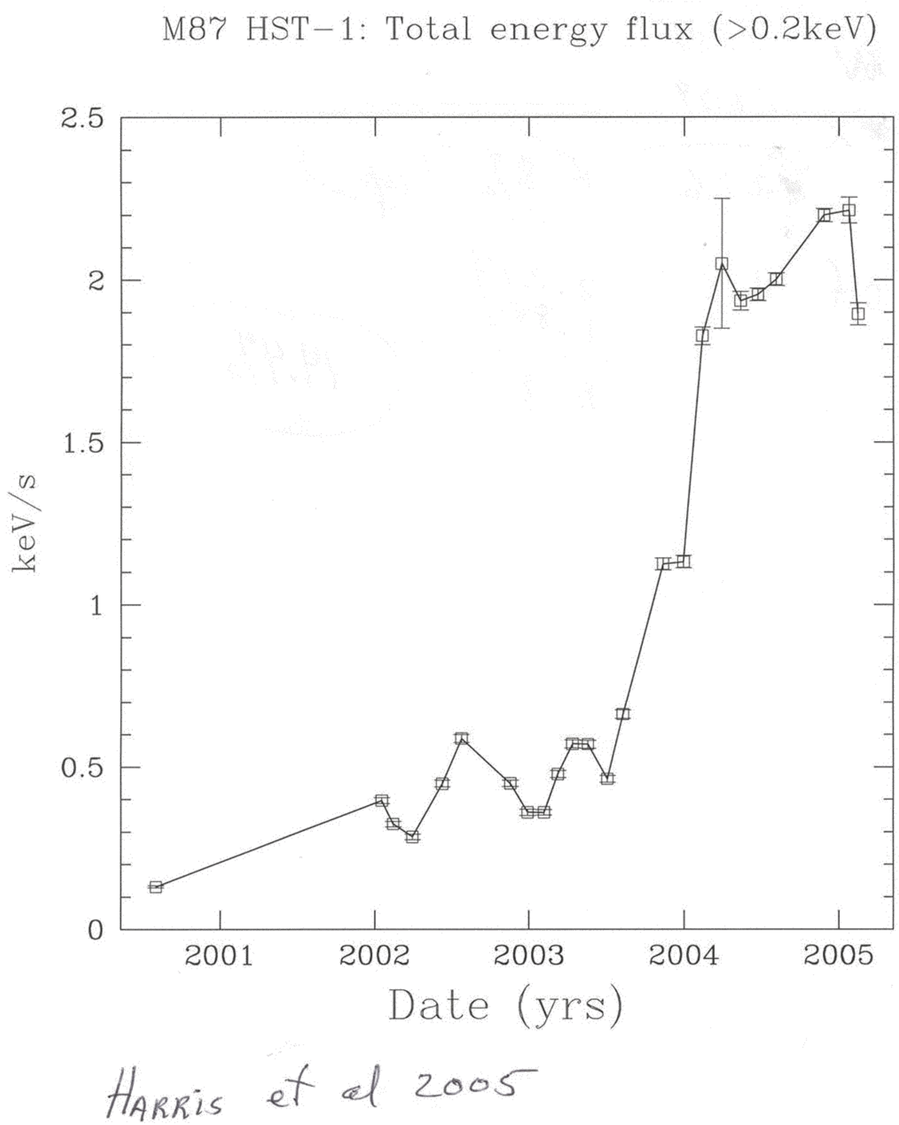
where M_d is the mass of the disk matter inside r_0. Thus $r_0(t) = r_0(0)(1 - t/t_{clps})^{2/3}$, where $t_{clps} = \sqrt{GM}\ M_d[r_0(0)]^{3/2}/(3\Psi_0^2)$ is the time-scale for collapse of the inner disk, and $r_0(0)$ is the intial radius of O-point of the magnetic field. The analysis breaks down when $r_0(t)$ reaches the inner radius of the disk r_i at time a $t_{max}/t_{clps} = 1 - [r_i/r_0(0)]^{3/2}$.

The power output to the Poynting jets is

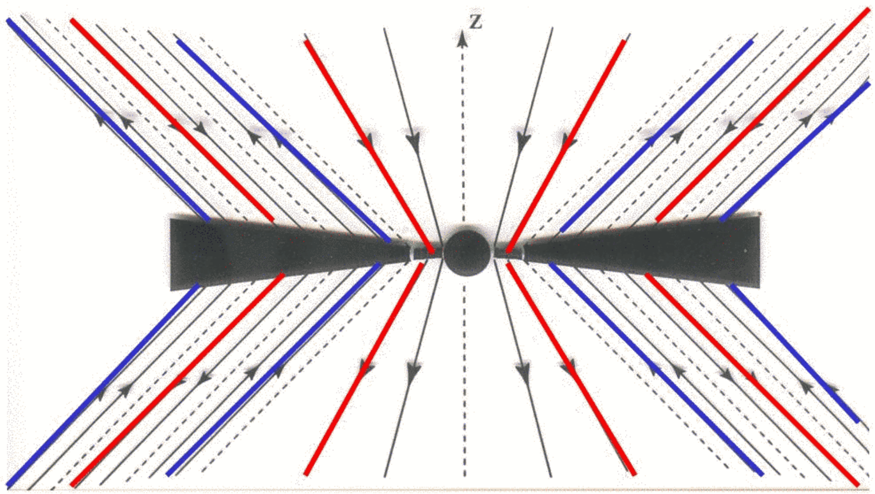
$$\dot{E}(t) = \frac{2}{3}\frac{\Delta E_{tot}}{t_{clps}}\left(1 - \frac{t}{t_{clps}}\right)^{-5/3} \ ,$$

where $\Delta E_{tot} = GMM_d/2r_i$ is the total energy of the outburst. Roughly, $t_{clps} \sim 2\ \mathrm{day} M_8^2(M_d/M_\odot)(6 \times 10^{32}\mathrm{Gcm}^2/\Psi_0)^2$ for $r_i = 6GM/c^2$.



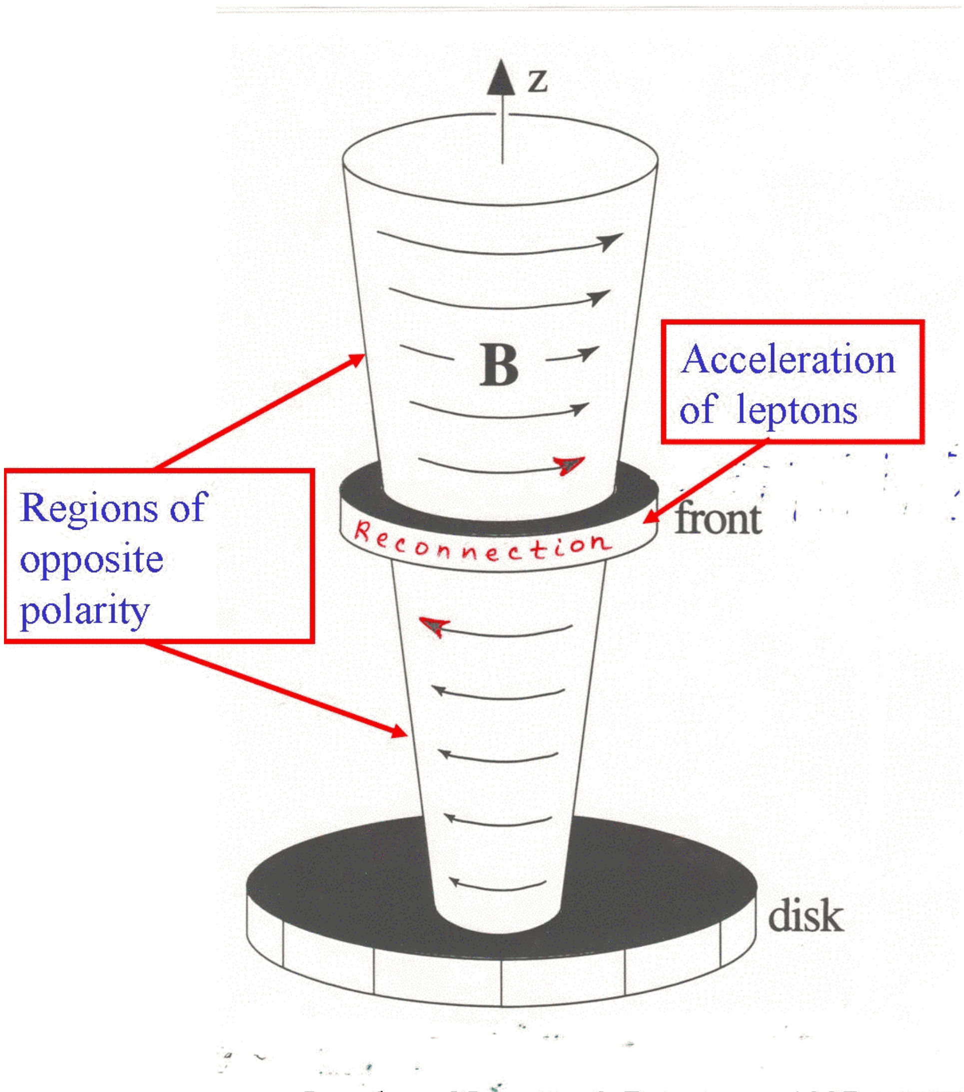


Zebra-stripe Magnetic Field



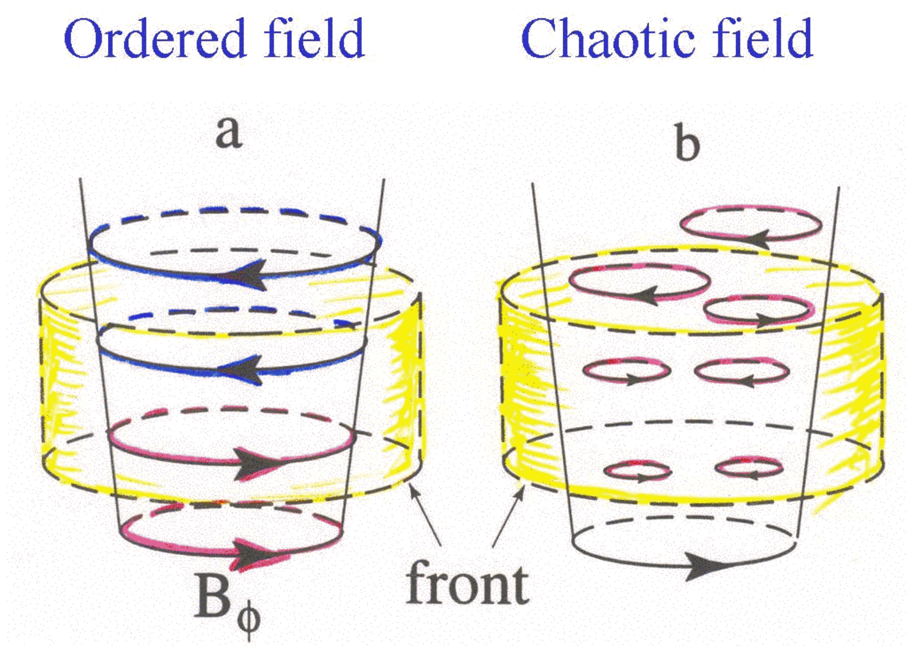
Magnetic field changes polarity

Lovelace, Newman, & Romanova 1997



Lovelace, Newman & Romanova 1997

Accelration of Particles



Romanova 1998, IAU proceedings
Begelman – importance of the chaotic magn. field

Conclusions

Ordered magnetic fields may be important in the origin of jets and outflows

Opening of the loops in the disk may lead to both: Poynting flux and hydromagnetic outflows

Regions of enhanced magnetic fields may lead to global magnetic instability of the disk and implosive accretion

Loops have opposite polarity: may lead to the release of magnetic energy in the front