Acceleration of plasma outflows from compact astrophysical sources

V.S.Beskin, E.E.Nokhrina

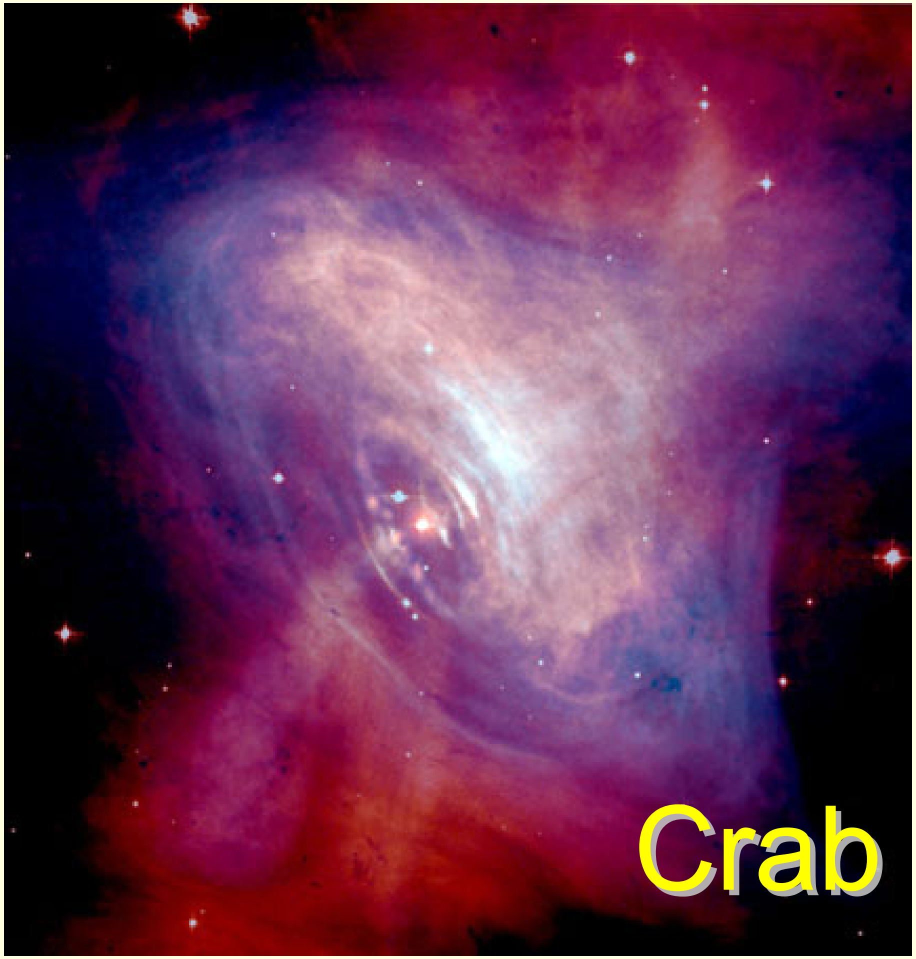
MNRAS, 2006, Vol.367, 375-386
astro-ph/0506333v2

Plan

- Introduction
- The effective acceleration of plasma outflow
- Astrophysical application: pulsars
- Conclusions

Introduction

- The theory implies magnetically-dominated flow in the vicinity of pulsar, as the observations show the matter-dominated regime in the outer magnetosphere.
- How does this transition occur ?



General approach (problems)

- The full MHD problem (even ideal and axisymmetric) requires solving the mixed-type second-order partial differential equation with 5 *a priori* unknown integrals of motion, which is a formidable task. However
- there are a few known force-free solutions that we can use as a zero approximation, when the flow is still magnetically dominated.
- We can be sure that the magnetically dominated solutions exist up to the fast magnetosonic surface.
- Downstream the FMS the problem needs investigation.

Monopole magnetic field

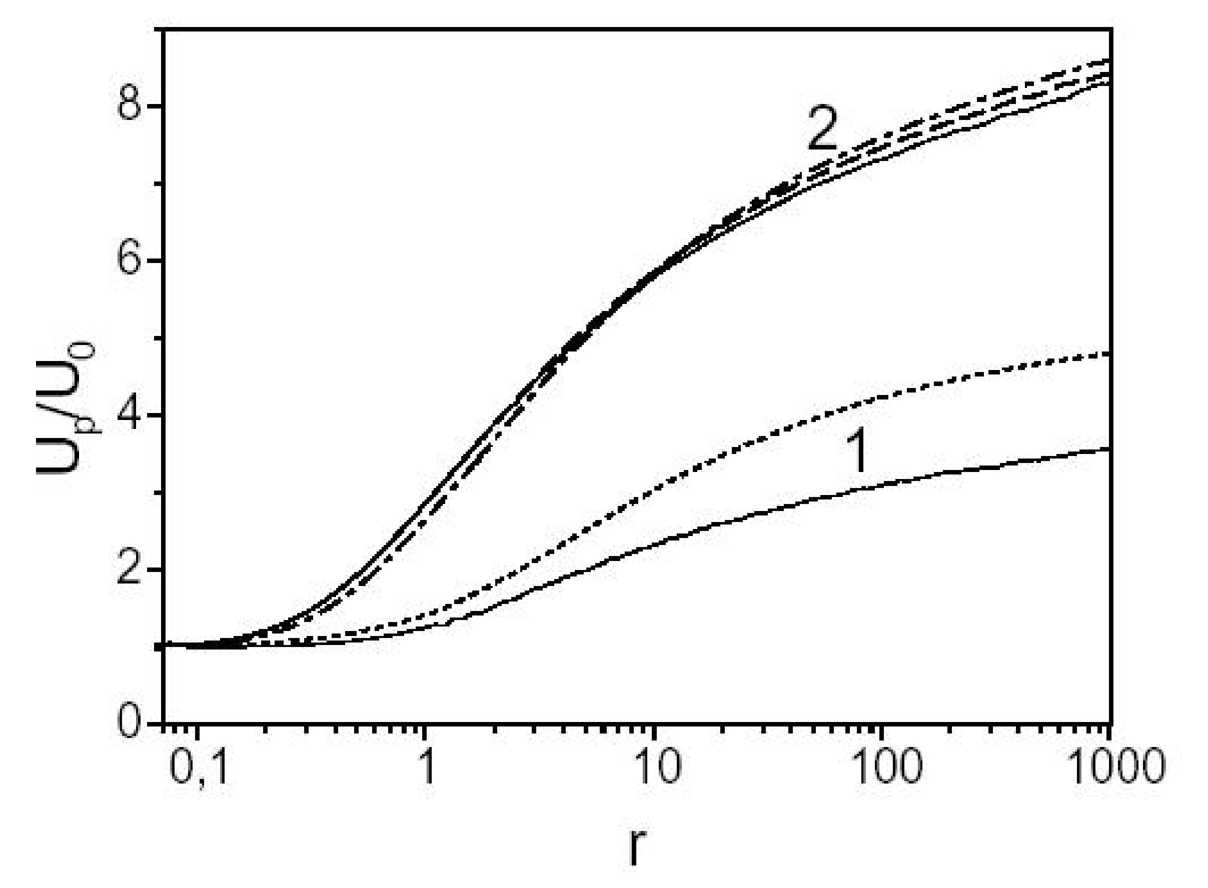
- The FMS is located at the final distance, with Lorentz factor

$$\gamma = \sigma^{1/3}$$

- In the monopole magnetic field (Michel solution) there is a very slow acceleration in the far region (Beskin, Kuznetsova & Rafikov, 2000; Bogovalov 2001) :

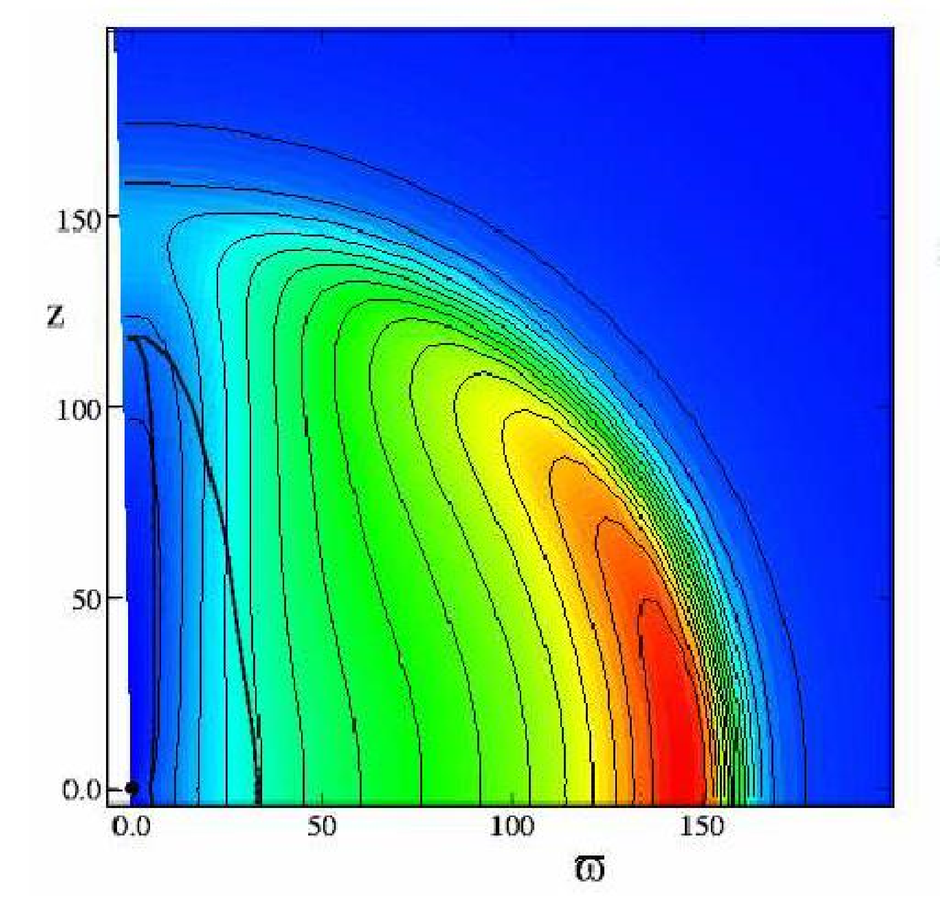
$$\gamma = \ln^{1/3} r$$

Monopole magnetic field



Bogovalov, 2001

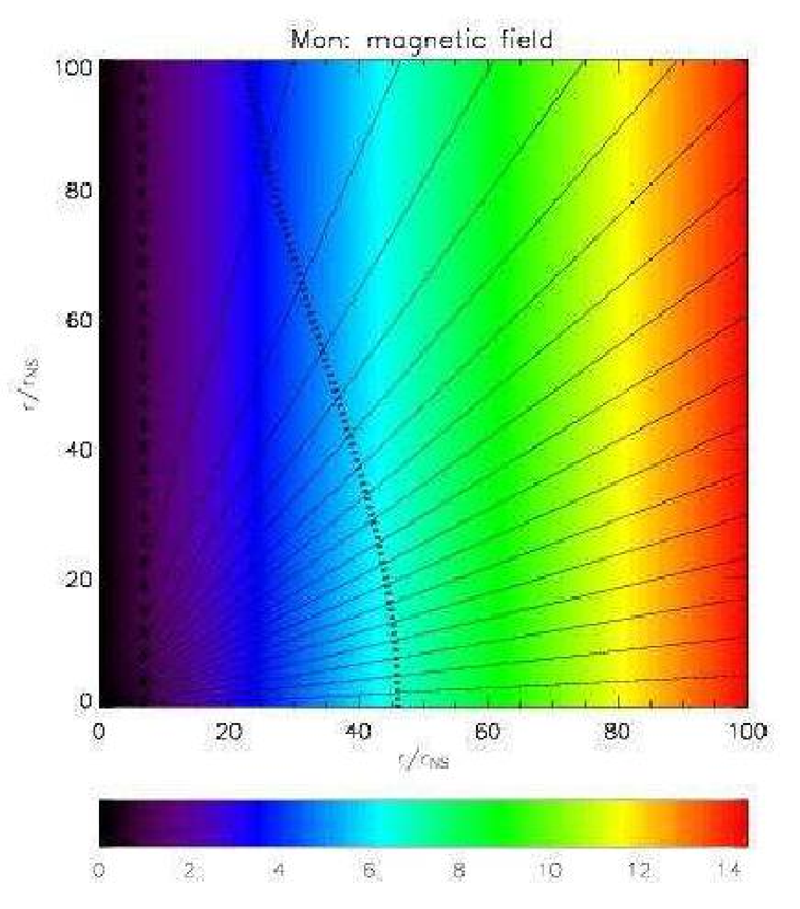
Monopole magnetic field



Komissarov, 2005

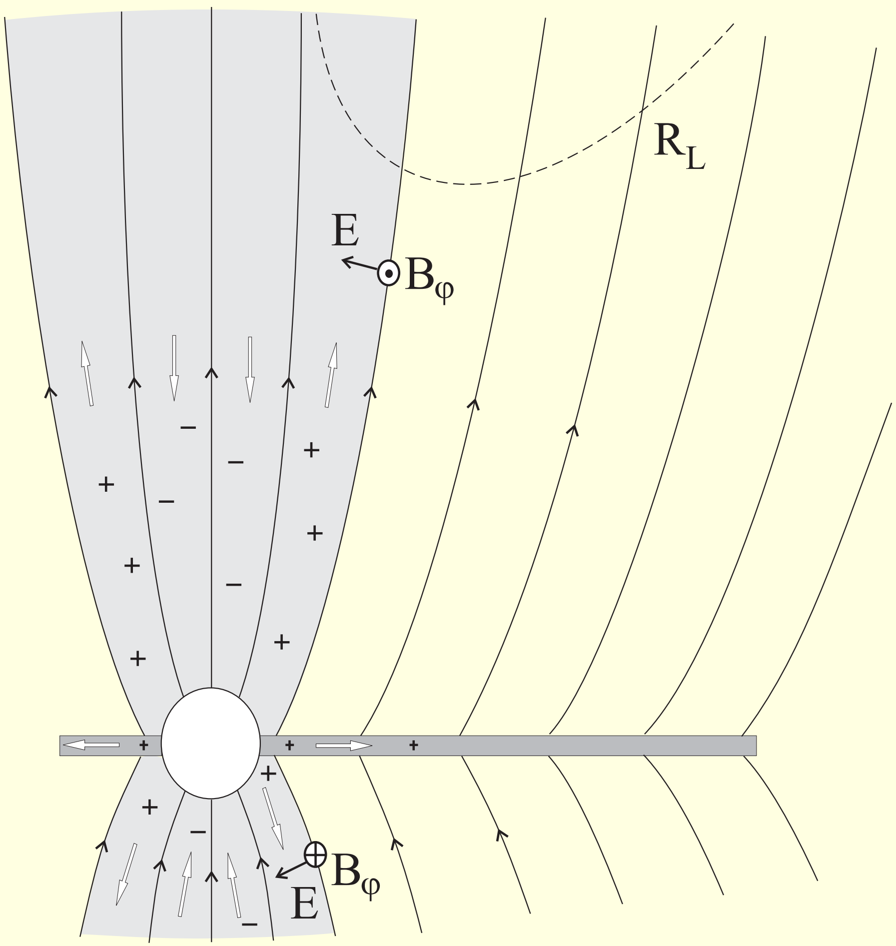
Monopole magnetic field

Bucciantini, Thompson, Arons, Quataert, Del Zanna, 2006



Parabolic magnetic field (model)

- The zero approximation – force-free flow in the parabolic magnetic field (Blandford, 1976)
- The flow is well collimated even in the zero approximation



Parabolic magnetic field (model)

- We assume the “working volume” with the constant angular velocity of the magnetic surfaces, and with the velocity obtained by Blandford and Znajek, 1977.
- The outer field — either the vacuum parabolic magnetic field or slow ion wind originating from the disk rotating with Keplerian velocity, supported by the vacuum field.

Parabolic magnetic field (results)

- The Lorentz factor at the FMS does not exceed the "classical" value

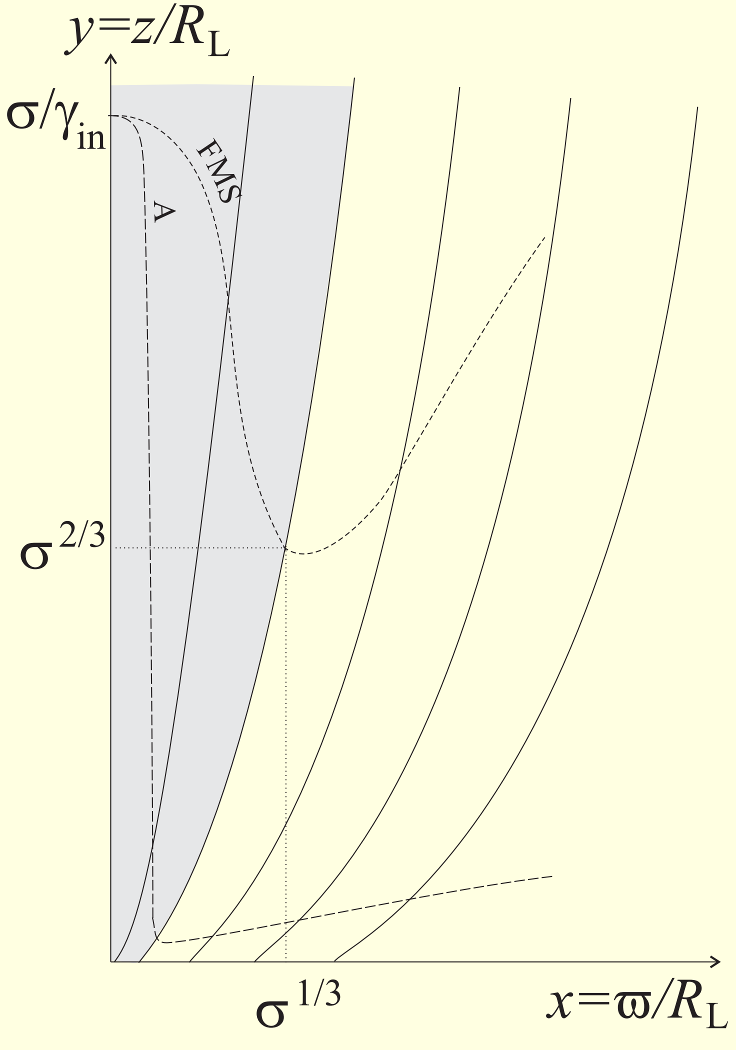
$$\gamma = \sigma^{1/3}$$

- Downstream the FMS the acceleration continues as

$$\gamma = x = z^{1/2}$$

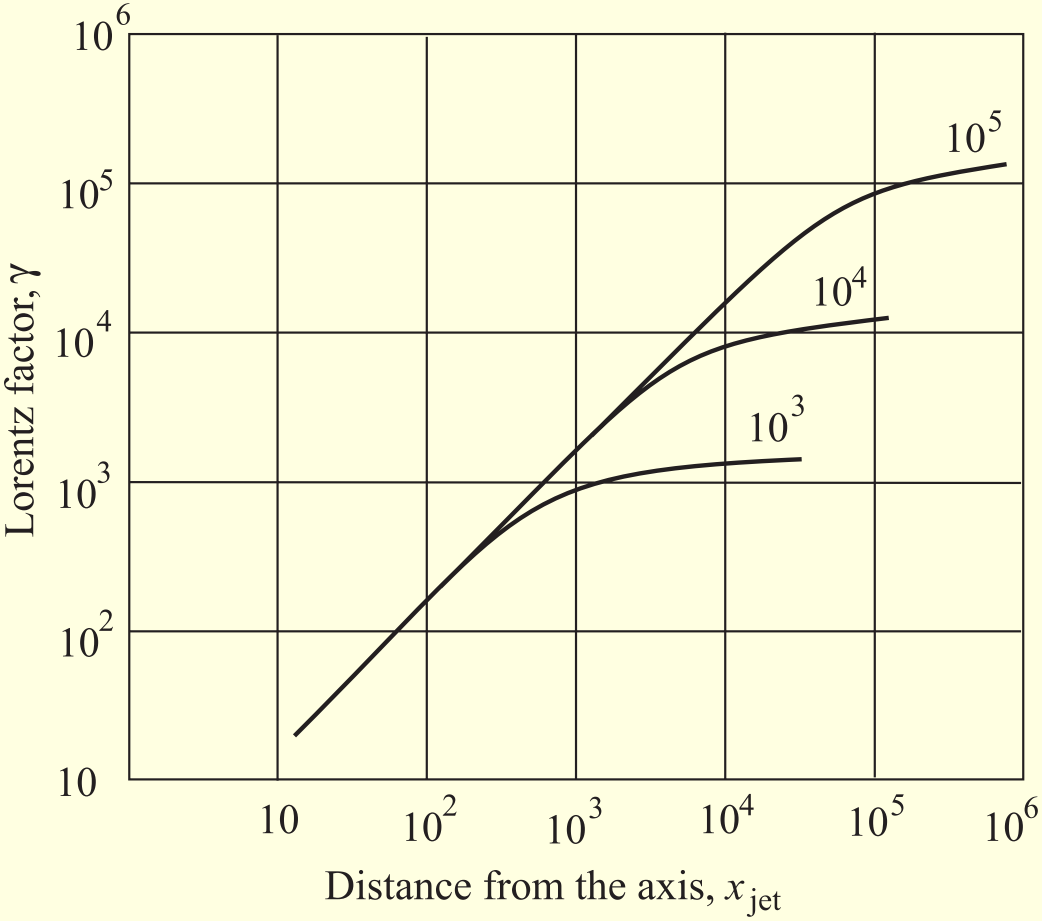
- The maximal Lorentz factor

$$\gamma \geq \sigma$$



Parabolic magnetic field (results)

The result of numerical integration of system of ODEs for different values of σ: 10^3, 10^4, 10^5.



Parabolic magnetic field (results)

- Downstream the FMS the flow can be regarded as one-dimensional.
- An exact solution for the approximate system of ODEs was obtained

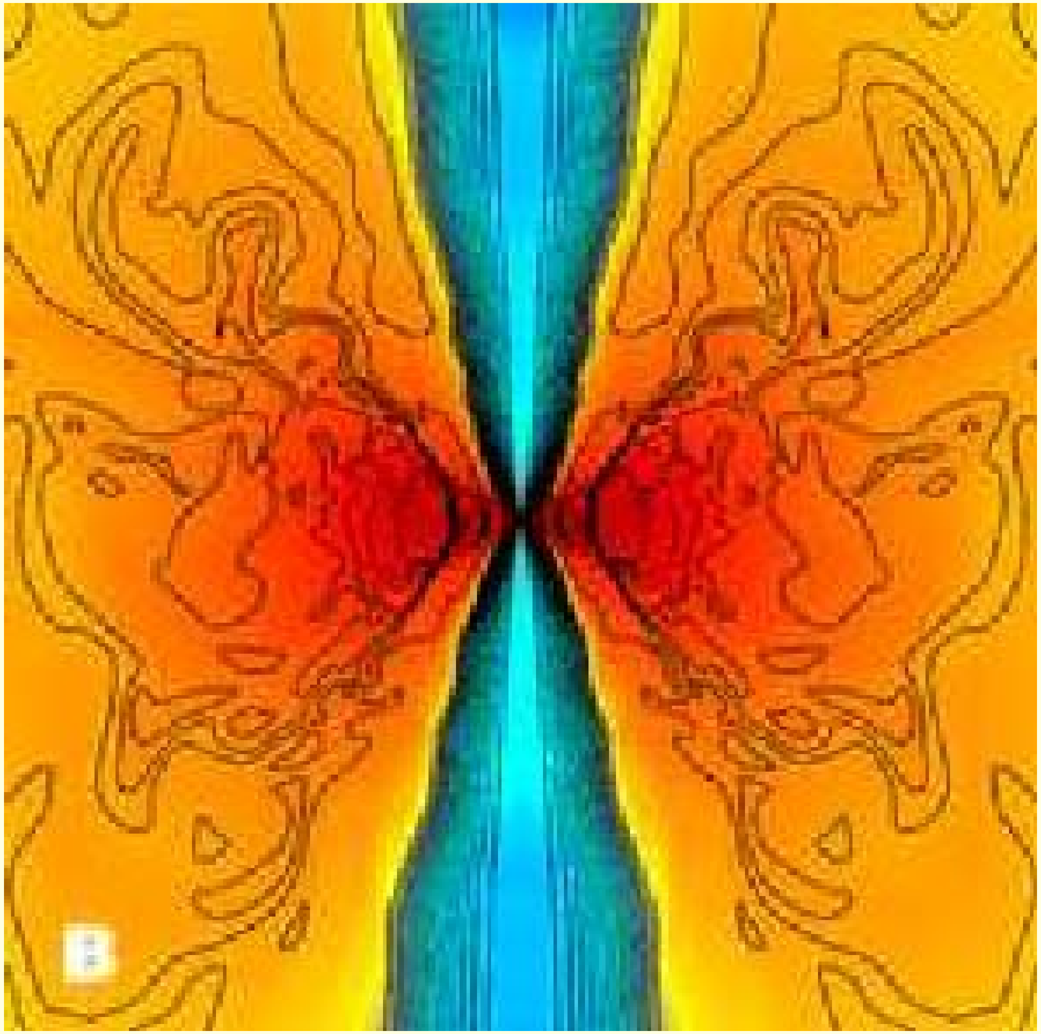
$$\gamma \propto x^{2/(1+M_0^2/\gamma_{in}^2)}$$

- So when the exponent is equal to ½,

$$\gamma = \frac{3}{2}\sigma$$

Parabolic magnetic field (numerical results)

The numerical simulation (MacKinney, 2006):

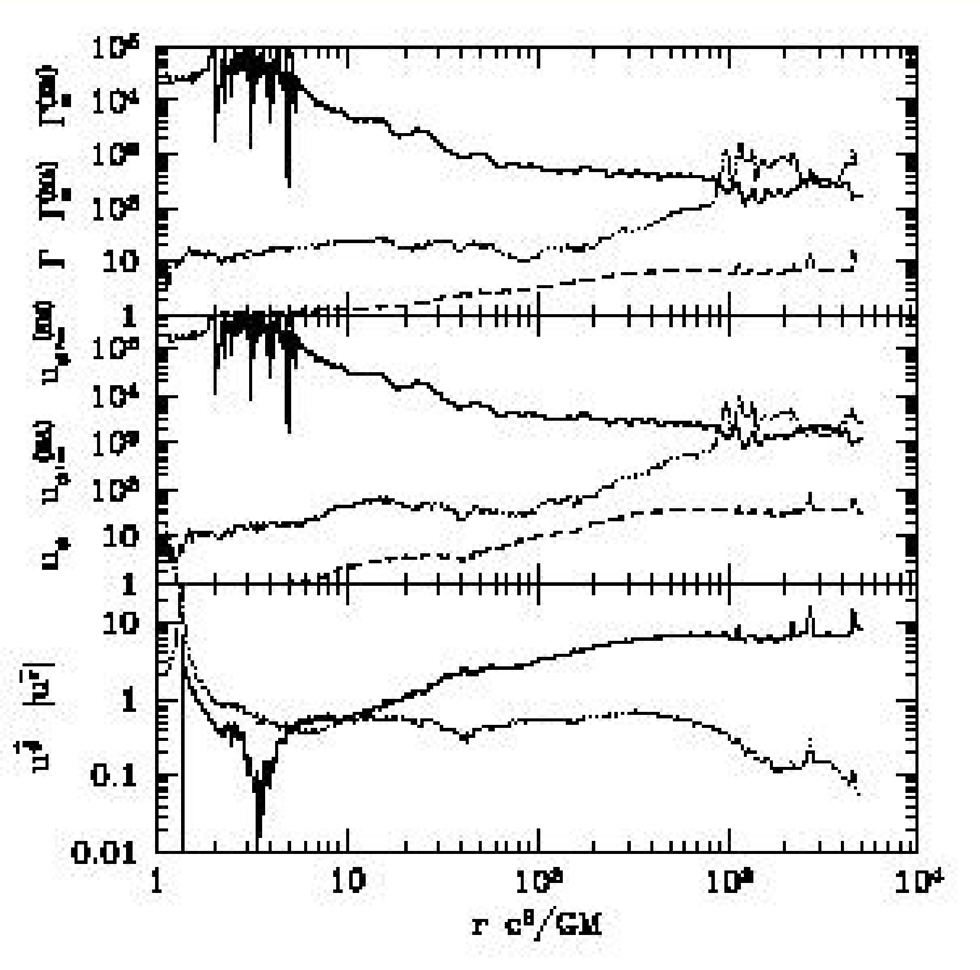


Parabolic magnetic field (numerical results)

- Our prediction:

$$\gamma = x \Rightarrow u_{\varphi} = 1$$

- The numarical simulation by MacKinney:



Astrophysical application: pulsars

- Although presented here model of axisymmetric flow in the presence of disk is more appropriate for the jets from black holes, it gives us a clue that the ideal MHD mechanism may account for the plasma flow acceleration in the pulsar magnetosphere
- Another mechanism of plasma outflow acceleration is possible: an existance of the light surface |E|=|B| in the vicinity of the the light cylinder (see poster B10)

Conclusions

- In the approach of ideal axisymmetric magneto-hydrodynamics it is possible to accelerate the plasma outflow to high Lorentz factors ($\gamma \geq \sigma$). However the presented model may be applied rather to the jets around black holes than to explain matter-dominated regime in the pulsar outer magnetospheres.
- Other acceleration mechanisms: reconnection in the striped wind, and the possible existence of the light surface E=B at the finite distance from the pulsar.