Acceleration of plasma outflow in the parabolic magnetic field

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Summary

The problem of effective transform of Poynting flux energy into the kinetic energy of relativistic plasma outflow in a magnetosphere is considered. We present an example of such acceleration. In order to perform it, we use the approach of ideal axisymmetric magetohydrodynamics (MHD). In particular, for highly magnetized plasma outflow we show that a linear acceleration $\gamma = \Omega r \sin\vartheta$ is a general result for any field configuration in the sub-magnetosonic flow. In the far region the full magnetohydrodynamics problem for one-dimensional flow is considered. It turns out that the effective plasma outflow acceleration is possible in the paraboloidal magnetic field. It is shown that such acceleration is due to the drift of charged particles in the crossed electric and magnetic field.

The general results

If we assume the flow to be highly magnetized in the vicinity of the central object, i.e. the magnetization parameter σ>>1, we can *always* find a solution of full MHD problem near the known force-free solution.

For any field structure the following always holds:

✓on the fast magentosonic surface

$$\gamma\,|_{FMS} \leq \sigma^{1/3}$$

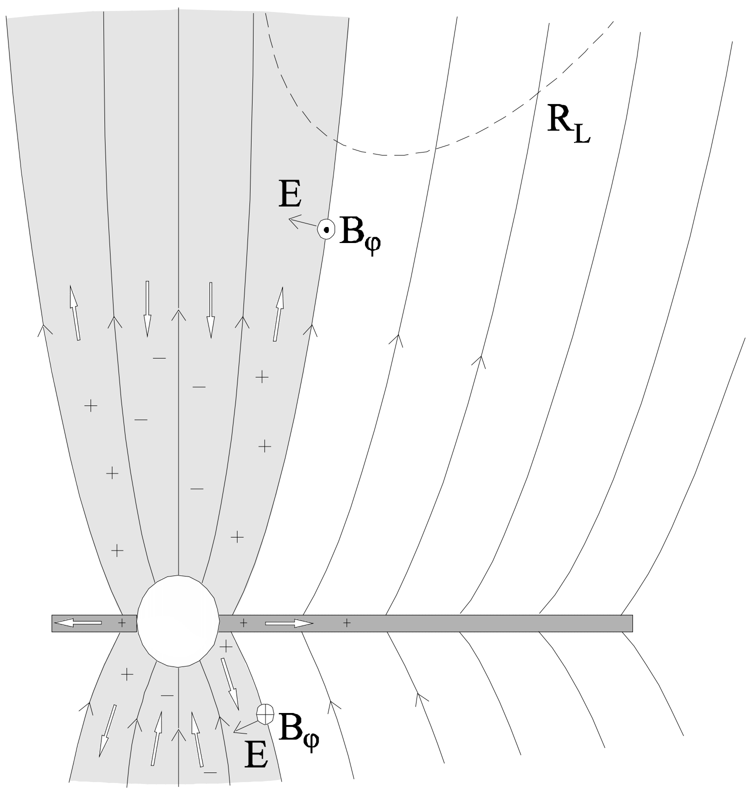
$$r\sin\vartheta\,|_{FMS} \leq \sigma^{1/3}$$

✓inside the FMS

$$\gamma = \Omega r \sin\vartheta$$

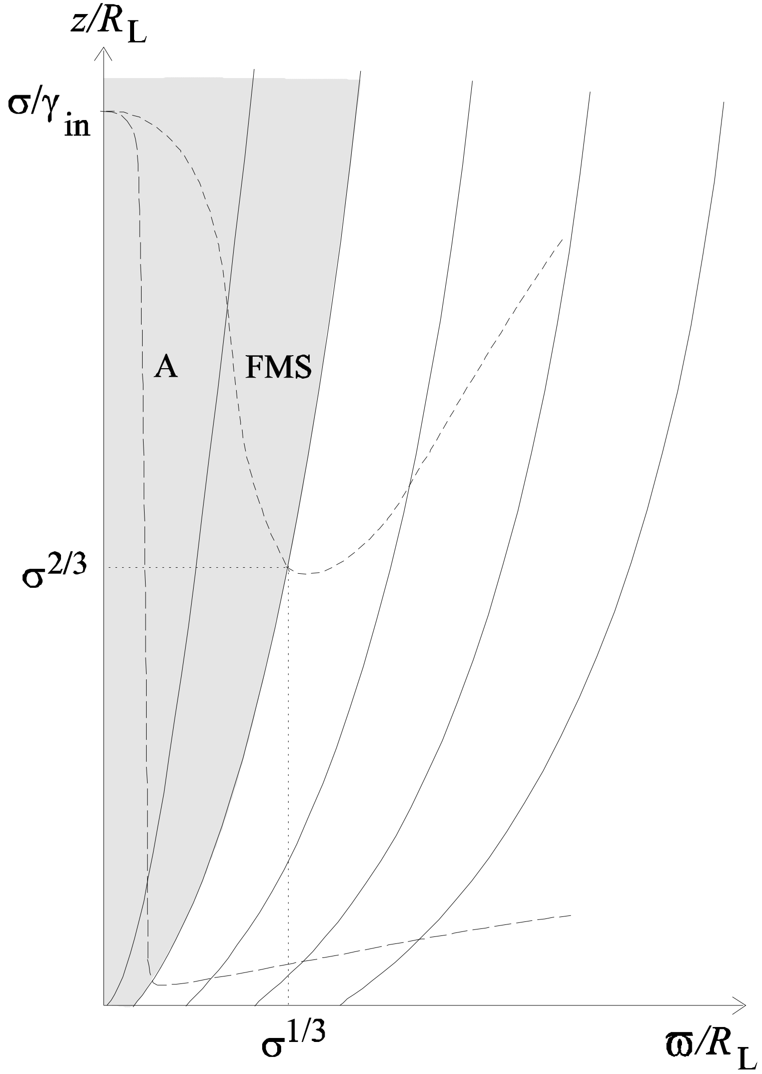
The zero approximation

The zero approximation — Blandford parabolic solution



Blandford force-free parabolic solution is taken as a zero approximation [1]. Here the thick arrows represent the volume currents. The shadowed region is the working volume $\Omega = const$.

Fast magnetosonic surface



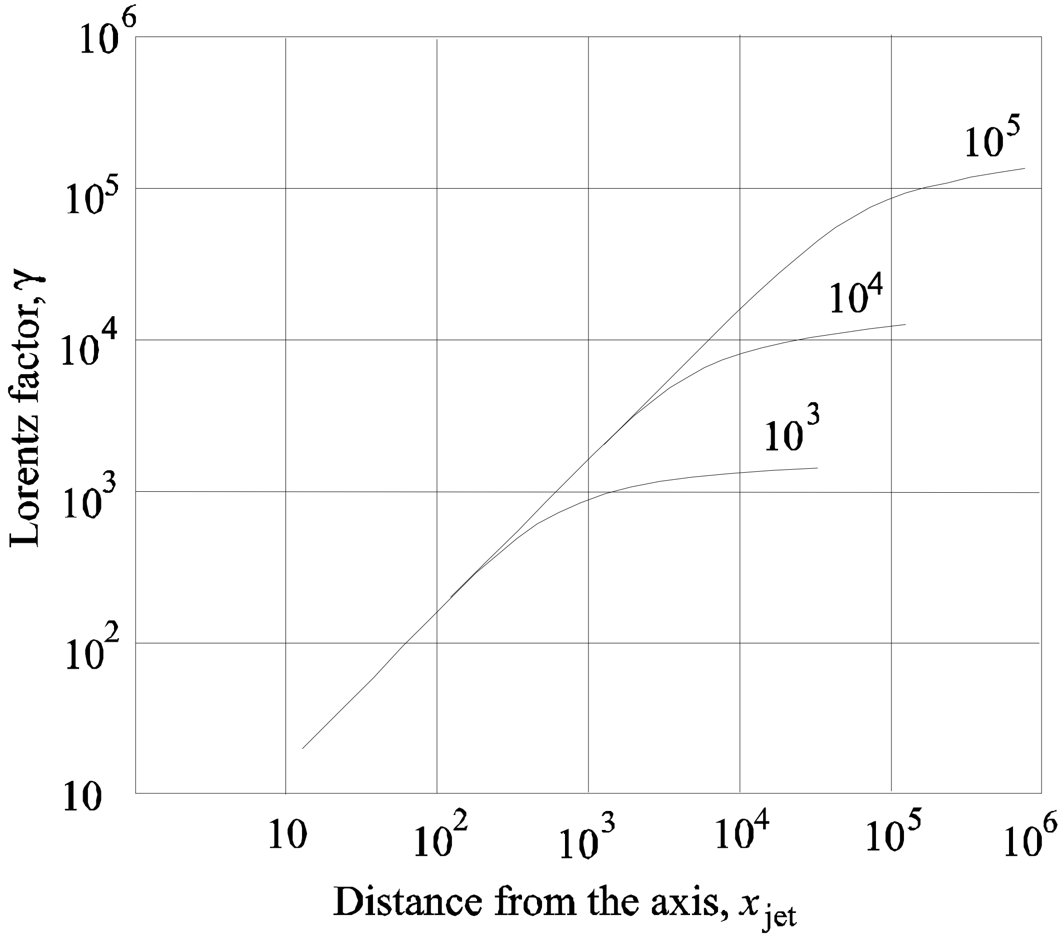
The position of FMS is

$$r_{FMS} = R_L \sqrt{\frac{\sigma}{\vartheta}} \ ,$$

with the Lorentz factor on FMS

$$\gamma = \sqrt{\sigma\vartheta} \ .$$

Super-magnetosonic flow



In the super-magnetosonic region the flow can be treated as one-dimensional [2]. In this case the full MHD problem can be formulated as a set of ordinary differential equations. The numerical integration gives the growth of Lorentz factor to the value

$$\gamma = \sigma ,$$

while its maximal value is

$$\gamma = 2\sigma$$

The numerical simulations

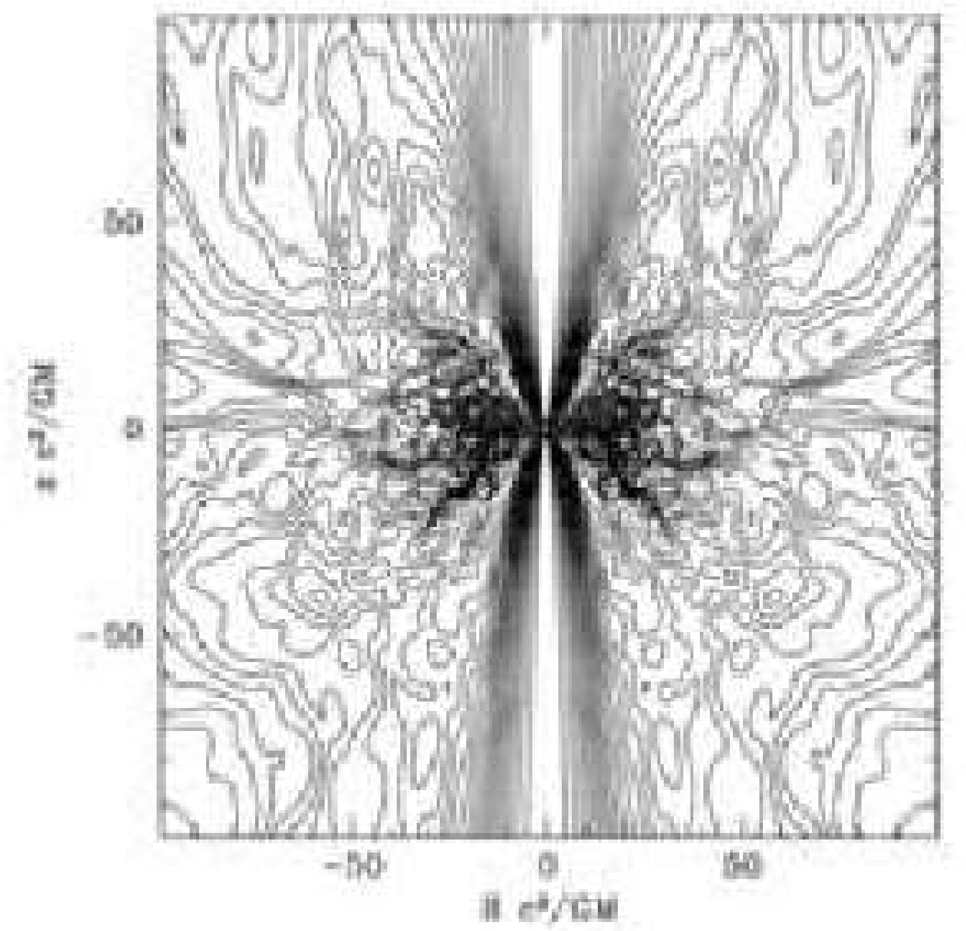


Figure 5. Field geometry near black hole for $t \approx 1500 t_g$ during phase of strong disk turbulence.

The recent numerical simulation of a jet was performed by McKinney [3]. The magnetic field turns out to be almost paraboloidal, and the Lorentz factor grows as $\gamma = \Omega r \sin\vartheta$, which is consistent with our result.

The drift in electric and magnetic fields

The drift velocity of particles in crossed electric and magnetic field is

$$\frac{v}{c} = \frac{|E|}{\sqrt{|B_P| + |B_\varphi|}},$$

or

$$\frac{v}{c} = \frac{1}{\sqrt{\frac{1}{(\Omega r \sin\vartheta)^2} + \left(\frac{|B_\varphi|}{|E|}\right)}}$$

If $|E| = |B_\varphi|$, the drift velocity gives for the Lorentz factor $\gamma = \Omega r \sin\vartheta$, so the plasma acceleration is effective. If this equality does not hold, the plasma velocity needed to screen the electric field in the particles' rest frame have to be much smaller. Thus, we may conclude that the plasma acceleration is due to the drift in the crossed electric and magnetic field.

Conclusions

- ✓Inside the FMS the Lorentz factor grows linear with the non-dimensional distance from the symmetry axis. This result does not depend on the particular magnetic field structure.
- ✓The value of Lorentz factor on the FMS is always $\gamma \leq \sigma^{1/3}$.
- ✓We have found that in the super-magnetosonic region in the parabolic magnetic field the effective plasma acceleration $\gamma = \Omega r \sin\vartheta$ continues until $\gamma = \sigma$, which corresponds to transformation of half on the Poynting flux into kinetic energy of plasma outflow.
- ✓We explain such acceleration as the drift velocity of particles in the crossed electric and magnetic fields.

Literature

1. Blandford, R.D.: Accretion disc electrodynamics - a model for double radio sources. MNRAS **176**, 465-481 (1976)
2. Beskin, V.S., Nokhrina E.E.: The effective acceleration of plasma outflow in the paraboloidal magnetic field. MNRAS, **367**, 375-386 (2006)
3. McKinney, J.C.: General relativistic magnetohydrodynamic simulations of jet formation and large-scale propagation from black hole accretion system. arXiv:astro-ph/0603045v1