Buoyancy of relativistic magnetic flux tubes and Penrose process produce jets from Kerr black holes

V. S. Semenov, S. A. Dyadechkin, and M. F. Heyn

Citation: AIP Conference Proceedings **1606**, 66 (2014); doi: 10.1063/1.4891117

View online: http://dx.doi.org/10.1063/1.4891117

View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1606?ver=pdfcov

Published by the AIP Publishing

Buoyancy of relativistic magnetic flux tubes and Penrose process produce jets from Kerr black holes

V. S. Semenov*, S. A. Dyadechkin†,* and M. F. Heyn**

*Saint Petersburg State University, Petrodvoretz, 198504, Russia
†Finish Meteorological Institute, Helsinki, Finland
**Institute for Theoretical and Computational Physics, TU-Graz, Austria

Keywords: <jet, string, black hole>
PACS: 98.62.Nx,98.62.Js,98.62.En

INTRODUCTION

The exact mechanism by which astrophysical jets from Active Galactic Nuclei (AGN) are formed is still poor understood. It is believed that necessary elements are a rotating (Kerr) black hole and a magnetised accreting plasma [1, 2]. Sometimes plasma embedded in the magnetic field can be considered as a collection of non-linear strings (flux tubes) [3]. The simplest physical system producing the relativistic jet, is probably the mass loaded magnetic flux tube and the Kerr black hole [4].

MAGNETIC FLUX TUBE - NONLINEAR STRING

The string equations for a flux tube embedded in a gravitational field $g_{ik}(x^i)$ and a pressure field $P(x^i)$ can be derived from the action [4]

$$S = -\int \frac{Q}{\rho} \sqrt{g_{ik} x^i_\eta x^k_\eta}\, d\eta\, d\alpha, \tag{1}$$

where

$$P \equiv p - \frac{1}{8\pi} h^k h_k, \quad Q \equiv P + \varepsilon - \frac{1}{8\pi} h^k h_k, \quad h^i \equiv *F^{ik} u_k, \tag{2}$$

Here p is the plasma pressure, P is the total (plasma plus magnetic) pressure, ε is the internal energy, g_{ik} is the metric tensor with signature $(1,-1,-1,-1)$, h^k is the space-like 4-vector of magnetic field, u^k is time-like vector of the 4-velocity, η is the time-like parameter on the world sheet of the string $x^k(\eta,\alpha)$, α is the space like parameter, it has physical meaning of mass of the plasma inside the tube with unit magnetic flux in the proper frame of reference. The appropriate gauge condition is [5]

$$\sqrt{g_{ik} x^i_\eta x^k_\eta} = \frac{1}{w}, \tag{3}$$

where $w = \varepsilon + p/\rho$ is the enthalpy of the plasma. The coordinates η, α is introduced such that

$$x^i_\eta \equiv \frac{\partial x^i}{\partial \eta} = \frac{u^i}{w}, \; x^i_\alpha \equiv \frac{\partial x^i}{\partial \alpha} = \frac{h^i}{\rho} \tag{4}$$

Using the gauge condition (3) it can be shown that the equations of motion generated by the action (1) are the following

$$-\frac{\partial}{\partial \eta}\left(\frac{wQ}{\rho} x^l_\eta\right) - \frac{wQ}{\rho} \Gamma^l_{ik} x^i_\eta x^k_\eta + \frac{\partial}{\partial \alpha}\left(\frac{\rho}{4\pi w} x^l_\alpha\right) + \frac{\rho}{4\pi w} \Gamma^l_{ik} x^i_\alpha x^k_\alpha = -\frac{g^{il}}{w\rho} \frac{\partial P}{\partial x^i}, \tag{5}$$

where Γ^l_{ik} are Christoffel symbols. These equations are of hyperbolic type with relativistic Alfvénic and slow mode characteristics.

II Russian-Spanish Congress on Particle and Nuclear Physics at all Scales, Astroparticle Physics and Cosmology
AIP Conf. Proc. 1606, 66-70 (2014); doi: 10.1063/1.4891117

The Kerr metric in Boyer-Lindquist coordinates has two cyclic variables, the coordinate time t and the azimuth angle ϕ, which leads to conservation laws for the energy E and the angular momentum L of the string

$$E = \int \frac{Q}{w\rho}(g_{tt}t_\tau + g_{t\varphi}\varphi_\tau)d\alpha, \tag{6}$$

$$L = -\int \frac{Q}{w\rho}(g_{t\varphi}t_\tau + g_{\varphi\varphi}\varphi_\tau)d\alpha. \tag{7}$$

The string equations (5) have been solved numerically using the total variation diminishing (TVD) scheme. The conservation laws (6)-(7) have been used to control the accuracy of the numerical scheme. More details on the method can be found in [5].

FORMATION OF THE RELATIVISTIC JET

Let us consider an initially straight magnetic flux tube with zero angular momentum everywhere along the string (Fig.1a). If this would be just a convected fluid tube without magnetic field, each part of the tube would start to spin up with the Zero Angular Momentum Observer (ZAMO) angular velocity as it falls into the black hole.

Due to the differential rotation of the Kerr metric, the flux tube becomes stretched and twisted (Fig.1b). The increase of magnetic tension slows down the rotation of the central part of the tube nearest to the black hole and therefore the latter will rotate locally slower than ZAMO and thus gain negative energy and momentum. After a while negative angular momentum, as well as negative energy appears in this leading part of the tube (depicted in red in Fig.1).

Since the total energy of the tube is conserved, some outer part of the tube will have now more energy than it was initially. The whole process is similar to the Penrose process [6] but in the string mechanism there is no need for the decay of particles because angular momentum and energy can be redistributed along the tube via MHD waves.

In the course of time the process of field line stretching continues, i.e. the magnetic field strength increases whereas the density decreases. Then, another physical process plays an important role: the part of the flux tube with extra positive energy looses more and more plasma and the flux tube will feel the relativistic analogon of the buoyancy force. This force first slows down the radial plasma accretion and then eventually pushes some fragment with positive extra energy along the spin axis outside the static limit surface as shown in Fig.1. This is the birth of a jet. The buoyancy force generates the pronounced double helical magnetic field structure aligned with the spin axis. Along these field lines, the plasma is centrifugally accelerated to nearly the speed of light.

This process evidently leads to an unlimited stretching of the flux tube since one part of the string continues to fall into the hole and simultaneously another part of the string is pushed outward. Apparently at some time this stretching must be limited by some nonideal process, probably by magnetic reconnection. Most effectively this will work if the stretched flux tube is reconnected outside the static limit boundary to itself. A closed double helical structured field line with low density will form a bubble which will freely evolve and the release of magnetic tension will power the jet stream while the ergospheric part of the tube is supplied with new accreting material. The structure of the magnetic field inside the outgoing plasma bubble becomes more and more simple due to the relaxation of Maxwellian stresses and the double helical structure will relax into a simpler circular structure. As a consequence, the collimation effect becomes less and the width of the jet slowly increases. At some time, the magnetic field cannot confine the rotating plasma any more, and the jet quickly spreads out (Fig.2).

CONCLUSIONS

We model the formation of astrophysical jets using a relativistic version of the thin flux tube approximation in the Kerr black hole spacetime. Our simulations show the formation of a collimated bubble-structured relativistic jet as a consequence of buoyancy-related winding up and stretching of the flux tubes (nonlinear strings) within the ergosphere, and cutting due to reconnection.

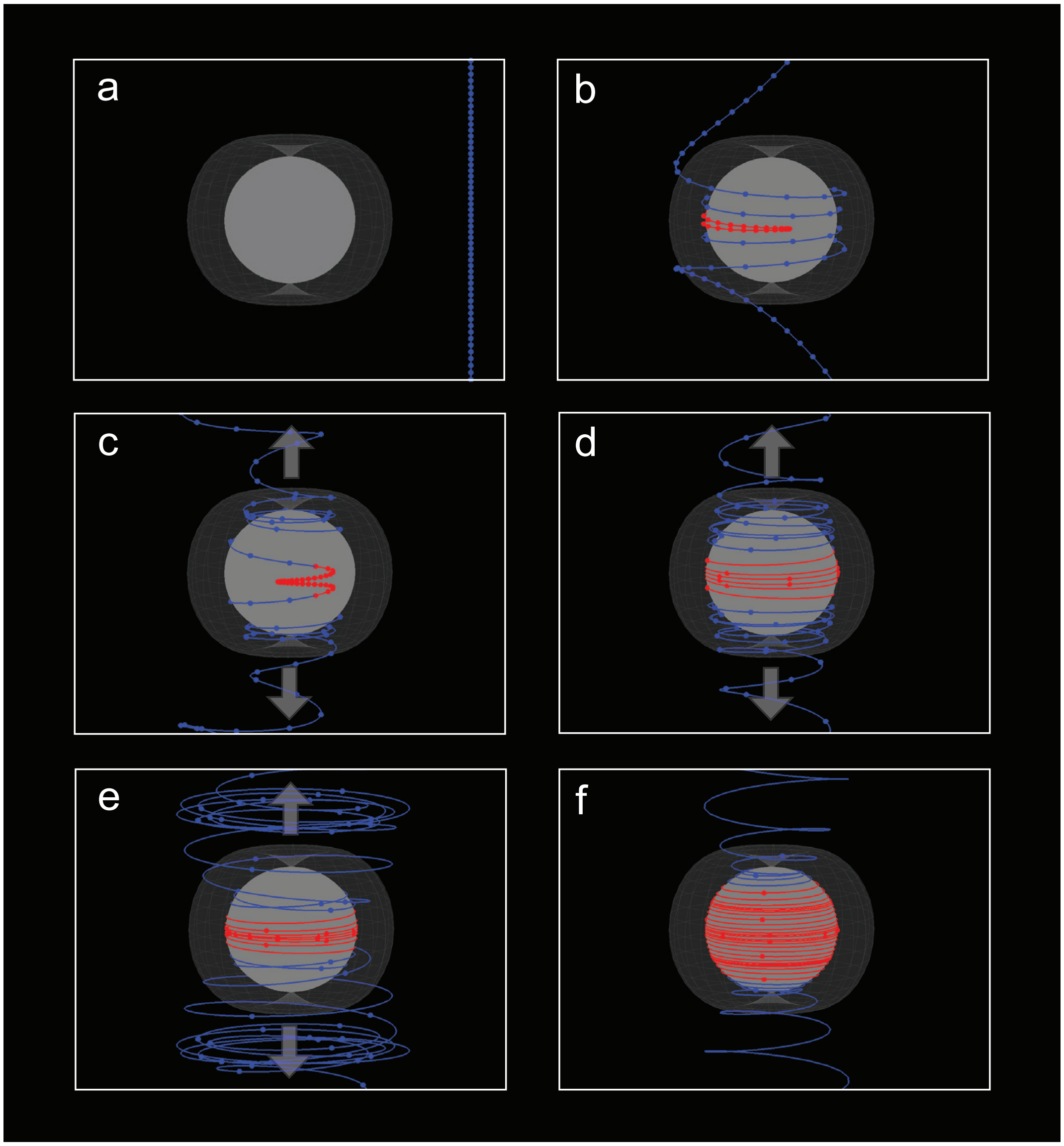

FIGURE 1. Differential rotation due to the Lense-Thirring effect near the Kerr black hole winds up the massive magnetic flux tube (a-d). Inside the ergosphere (light grey), magnetic tension slows down the rotation of the leading part of the tube marked in red. This part carries negative energy and angular momentum. Stretching of the flux tube is visualized by markers. The stretched field line has lower density and buoyancy produces the helical magnetic structure along the spin axis (e). Centrifugal forces accelerate the plasma along the field lines. This is the birth of the jet (f).

In our scenario the Penrose mechanism has been used twice. First, locally to redistribute angular momentum and energy along the string and, consequently, to extract energy from the Kerr black hole. Second, globally in form of an outgoing plasmoid which transfers additional positive energy and angular momentum away from the black hole which can be considered as a classical Penrose particle carrying away rotational energy from the black hole.

The animations are available at the geo.phys.spbu.ru/ ego.

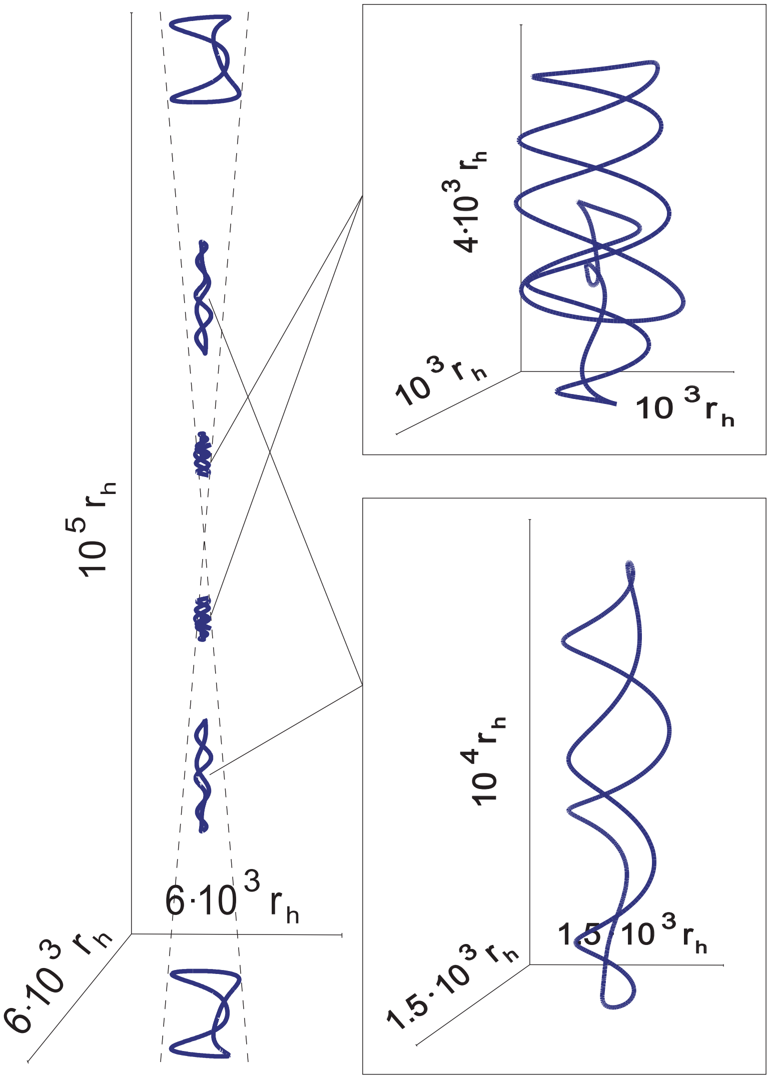

FIGURE 2. Reconnection outside the ergosphere produces magnetic bubbles with helical magnetic fields and a rotating plasma inside. Each plasmoid carries away rotational energy of the black hole similar to the outgoing particle in the Penrose mechanism. The evolution of such a plasmoid is shown for different time steps. The helical magnetic field relaxes into a simpler circular structure and, as a result, the collimation of the jet is lost in the final stage of evolution.

ACKNOWLEDGEMENTS

This work was partially supported by RBRF under grant 12-05-00918 and by the grant for support of leading scientific schools 2836.2014.5.

REFERENCES

1. R. D. Blandford and R. L. Znajek, *Mon. Not. R. Astr. Soc.*, **179**, 433–456 (1977).
2. R. Narayan, *New J. Phys.* **7**, 199–204 (2005).

3. N. V. Erkaev, H. K. Biernat, and C. J. Farrugia, *Phys. Plasmas* **7**, 3413-3420 (2000).
4. V. S. Semenov, *Physica Scripta* **62**, 123–126 (2000).
5. V. S. Semenov, S. A Daydechkin, and B. Punsley, *Science* **305**, 978–980 (2004).
6. R. Penrose and R. Floyd, *Nature Phys. Sci.* **229**, 177–179 (1971).