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Toy Model of Frame-Dragging Magnetosphere for the M87 Jet

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Abstract. We make a toy model for M87 jet to interpret its parabolic structure and acceleration in the apparent speeds, according to observations in milli-arcsecond to arcsecond scales upstream of HST-1. The outermost layer of jet is driven by the frame-dragging effect in the Kerr spacetime with a slowly to moderately spinning black hole. The corresponding magnetosphere has a foot-point R_0 in the vicinity of event-horizon, and rotating at a frequency Ω_F equal to that of the frame-dragging $\omega(R_0)$.

Key words. Black hole physics—magnetic fields—galaxies: individual (M87)—galaxies: jets.

1. Introduction

The proper motion profile of M87 jet, or the so-called apparent speeds $\beta_{\rm app}$ profile, was found to have significant acceleration from milli-arcsecond to arcsecond scales. Components in milli-arcsecond scales were found to be sub-luminal (Reid *et al*. 1989; Biretta & Junor 1995; Dodson *et al*. 2006; Ly *et al*. 2007), even $<0.07c$ (Kovalev *et al*. 2007). In the scales from 0.1 arcsecond to 1 arcsecond upstream of the feature HST-1 (Biretta *et al*. 1999), super-luminal components with $\beta_{\rm app} < 3.5c$ were detected (Asada *et al*. 2011). Interestingly, over the range of acceleration, the de-projected poloidal structure of M87 jet was found to maintain a narrow parabolic shape, i.e., $z \propto R^{1.73\pm0.05}$, which can be extrapolated to the vicinity of the central super-massive black hole (Asada & Nakamura 2012).

Theoretically, the relativistic jets/winds of active galactic nuclei are thought to be accelerated by black hole magnetospheres with poloidal structures of $z \propto R^{\xi}$ $(1 < \xi < 2)$ (Blandford 1976; Contopoulos 1995; Narayan *et al*. 2007; Komissarov *et al*. 2007). The magnetosphere is rotating at the angular frequency of the accretion disc, $\Omega_F = \Omega_{\rm disc}(R_0)$, which depends on the axial distance of the foot-point on the disc/equatorial plane R_0 (BP process, Blandford & Payne 1982). Alternatively, the magnetosphere is rotating comparable to but less than the black hole spinning frequency $\Omega_{\rm F} \lesssim \omega_{\rm BH}$, with the foot-point located on the horizon (BZ process, Blandford & Znajek 1977). In further studies of the latter case (Okamoto 1992, 2006), the black hole energy is thought to be extracted from a region of $\Omega_{\rm F} < \omega < \omega_{\rm BH}$, and the jet be initiated at a null surface where the magnetosphere is rotating at the frame-dragging frequency, i.e., $\Omega_{\rm F} = \omega(R_0)$.

In this paper, we are motivated to make a toy model of a magnetosphere, named as the frame-dragging magnetosphere which is located at the null surface. With a slowly to moderately spinning central black hole, this magnetosphere provides one kind of interpretation to the observed parabolic shape and acceleration of the M87 jet.

2. Modelling and results

In the force-free limit, the steady axisymmetric black hole magnetosphere is described by a stream function Ψ which satisfies

$$0 = \frac{1}{\alpha}\nabla_k \left\{ \frac{\alpha}{g_{\phi\phi}} \left[1 - \frac{g_{\phi\phi}}{\alpha^2}(\Omega_{\rm F} - \omega)^2 \right] \nabla^k \Psi \right\} + \frac{(\Omega_{\rm F} - \omega)}{\alpha^2} \cdot \frac{{\rm d}\Omega_{\rm F}}{{\rm d}\Psi}(\nabla\Psi)^2 + \frac{H^{\phi}}{\alpha^2}\frac{{\rm d}H_{\phi}}{{\rm d}\Psi}, \quad (1)$$

where α is the lapse function and ∇ is the covariant derivative operator in absolute space with Kerr metric in Boyer–Linquist coordinates. $\Omega_{\rm F}$ and H_{ϕ} (Komissarov 2004) are conserved quantities on the surface of each magnetosphere. $\Omega_{\rm F}$ is equal to $\omega(R_0)$ with a foot-point R_0 and a black hole spin parameter a is selected. As a first step, we adopt the self-similar forms of $\Psi = r^{\nu} P(\theta)$ and $H_{\phi} = h_0 \Omega_{\rm F}(\Psi)\Psi$ with constants ν and h_0. With a specific location of the outer light surface ($r_{\rm LS}, \theta_{\rm LS}$), the constants are calculated as

$$\nu \approx 2 - \frac{2}{\xi}, \quad h_0 \approx \frac{\nu}{\sqrt{1-\nu}} \left[\left(\frac{h_1 + \cot\theta_{\rm LS}}{\sqrt{h_1^2 + 1} - \sqrt{\cot\theta_{\rm LS}^2 + 1}} \right)^2 - 1 \right]^{\frac{1}{2}};$$

$$h_1 = -\cot\theta_{\rm LS} + \frac{2(\partial_R z)_{\rm LS}(\cot\theta_{\rm LS}^2 + 1)}{\cot^2\theta_{\rm LS} + 1 - [(\partial_R z)_{\rm LS} - \cot\theta_{\rm LS}]^2}. \quad (2)$$

The solution is then identified for a magnetosphere with poloidal structure of $z \propto R^{\xi}$, fixed by observations.

For example, we choose $R_0 = 2R_{\rm S}$, where $R_{\rm S}$ is the Schwarzschild radius, as the foot-point of the frame-dragging magnetosphere on the equatorial plane. This foot-point is located very close to the black hole, within the Innermost Stable Circular Orbit (ISCO) if $a < 0.5$. A steady Keplerian-like accretion flow cannot sustain at this radius to drive the magnetosphere. Thus, it is reasonable to assume the magnetosphere to be driven by the frame-dragging effect. In addition, since the observed emission is thought to come mostly from the sheath (Kovalev *et al.* 2007 and references therein), we assume that the outermost layer of the M87 jet is based at this magnetosphere. This indicates that the jet could be launched from a region

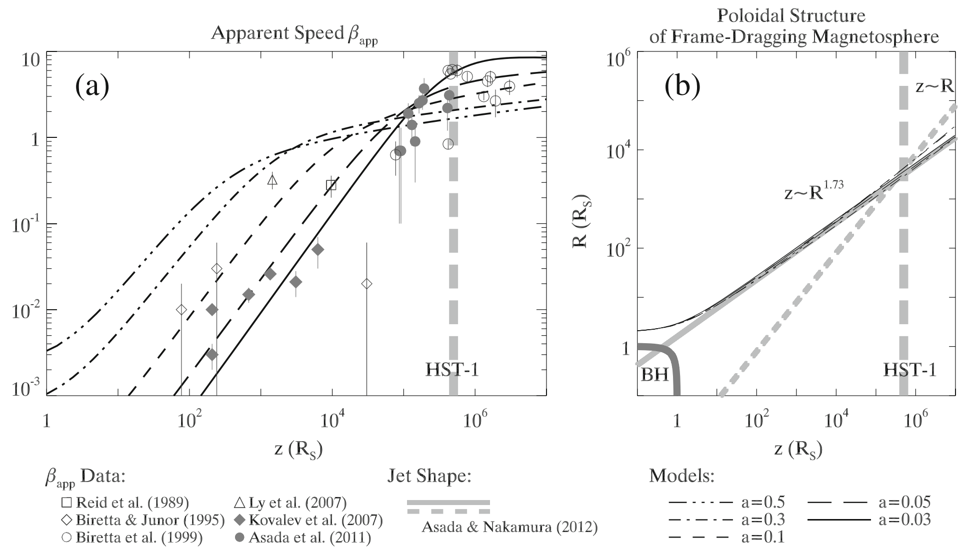

Figure 1. Five examples of the frame-dragging magnetospheres with the same foot-point $R_0 = 2R_S$ but different black hole spins a. They well interpret the acceleration (**a**) and the parabolic shape (**b**) of M87 upstream of HST-1.

$R_{BH} < R < R_0$. This region is consistent with the component of $5.5R_S$ in diameter, resolved by the latest VLBI observations at 1.3 mm wavelength (Doeleman *et al.* 2012).

We show solutions of five models in Fig. 1, with black hole spins $a = 0.5, 0.3, 0.1, 0.05$ and 0.03, respectively. The de-projected distances from the core/black hole z are shown in units of R_S, with the black hole mass $6.6 \times 10^9 M_\odot$ (Gebhardt *et al.* 2011), distance to Earth 16.7 Mpc (Jordán *et al.* 2005), and the angle of the jet axis to our line-of-sight 15° (Wang & Zhou 2009) adopted. The apparent speeds are calculated by the Poynting flux along the jet measured by a stationary observer at infinity (MacDonald & Thorne 1982; Komissarov 2004), by considering the projection effect. They generally interpret the sub-luminal speeds in milli-arcsecond scales ($10^{2\sim3} R_S$) and the acceleration upstream of HST-1 (Fig. 1a). The poloidal structures well interpret the observed parabolic shape upstream of HST-1 (Fig. 1b), where the thick solid and dashed grey lines represent the two fitting lines of the jet shapes in Asada & Nakamura (2012).

3. Discussions

The central engine of the M87 jet is considered to be one of the best super-massive black hole candidates. The highly-resolved jet shape and significant acceleration in the apparent speed stimulate us to investigate its jet formation. The toy model of the frame-dragging magnetosphere we made for the M87 jet is just a first step. It provides one kind of interpretation to observations upstream of HST-1. A full general relativistic magneto hydrodynamical treatment is necessary in the future to improve the limitations in this work, e.g., the force-free limit and the lack of study in cases with fast-spinning black holes.

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