*Black Hole Winds at All Scales*
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# Dynamics of M87 jet

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**Abstract.** Flows originating from black hole magnetospheres via Blandford-Znajek (BZ) process start highly relativistically, with very large Lorentz factors $\gamma_0 \gg 1$, imprinted into the flow during pair production within the gaps. As a result, BZ-driven outflows would produce spine-brightened images, contrary to observations of the edge-brightened jet in M87. We conclude that M87 jet is not BZ-driven.

**Keywords.** galaxies: active, jets, magnetic fields

## 1. Introduction

Observations of the inner part of the jet in M87 down to just 7 Schwarzschild radii shows limb brightened collimated jet - the jet accelerating smoothly, with a parabolic profile Nakamura & Asada (2013); Kim et al. (2018); Blandford et al. (2019), Fig. 1. This implies that a flow is only mildly relativistic. For example, estimates of the viewing angle $15^\circ - 30^\circ$ degrees Bicknell & Begelman (1996) imply bulk Lorentz factors $\sim 3 - 2$.

The Blandford & Znajek (1977) mechanism of AGN jet production involves pair production within the rotating black hole magnetosphere ensuing MHD acceleration. We point out (Lyutikov and Haitham, submitted) the dominant importance of plasma injection effects for relativistic winds from black holes. In the highly magnetized case (bead-on-wire) the motion of particles involves electromagnetic drift and motion along the spiral magnetic field. It turns out that a particle launched with large Lorentz factor along the rotating magnetic spiral (in a bead-on-wire approximation) moves nearly radially, Fig. 2.

Since the observed pattern is dominated by Lorentz boost, to calculate the images we employ the following procedure:

• Given the prescribed shape if field lines (e.g. parabolic) and for a given parallel Lorentz factor we calculate local Doppler factor $\delta$. In fact, since toroidal velocity is small, one can use just the shape of the flux surface to find the local direction of the flow.

• We scale local density (somewhat arbitrary) as $1/r^2$, total spherical distance to the black hole.

• local emissivity is parameterized as

$$j \propto \frac{\delta^3}{r^2} \tag{1.1}$$

• emissivity is integrated along the line of sight.

Our results demonstrate a consistent picture: relativistic flows emanating from within the magnetosphere are expected to produce spine-brightened images, Figs 2 and 4.

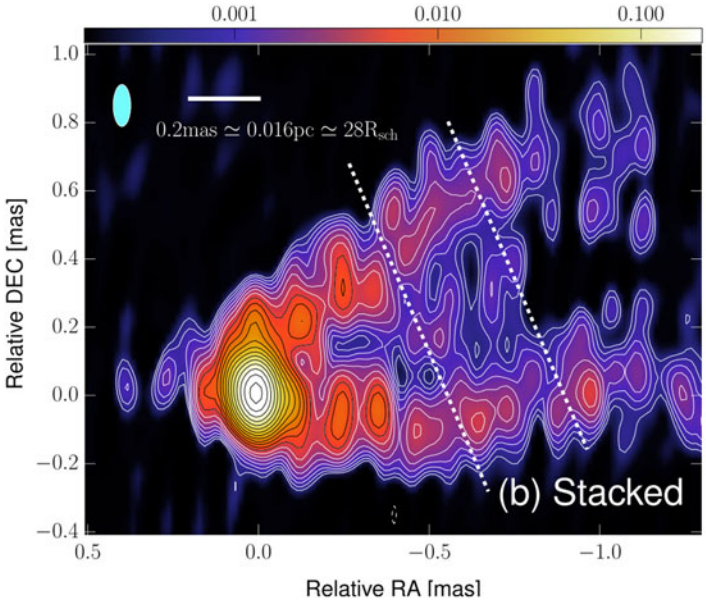


**Figure 1.** Central part of jet in M87, showing edge-brightened structure Kim et al. (2018).

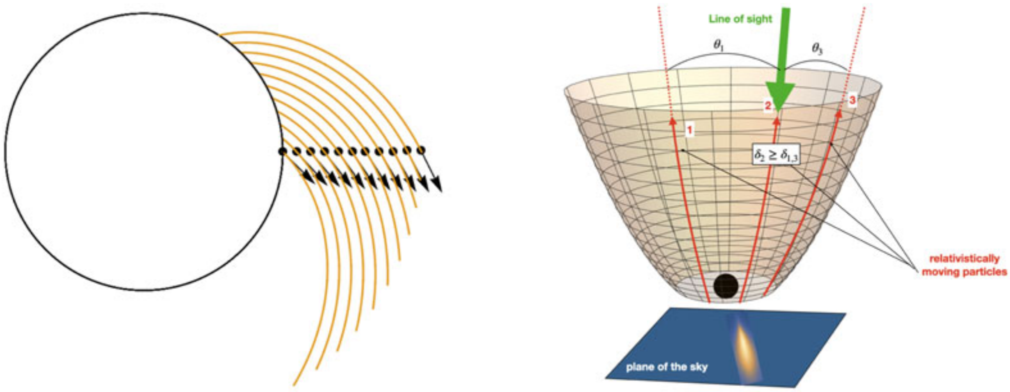


**Figure 2.** Left Panel: Particles' trajectories for Lorentz factors $\gamma_0 10$. The circle is the light cylinder, orange curves indicate the same magnetic field line at consecutive movements, arrows are directions of particle velocity at each point, and black dots are the location of the particle. These calculations illustrate that for $\gamma_0 \gg 1$ the trajectory is nearly radial. Graphic explanation why BH-produced jets are expected to be spine-brightened. Shown are flux surfaces and three different particles' trajectories. Emission produced by particle 2 has the smallest angle with respect to the line of sight, largest Doppler factor, and would result in brightest emission pattern.

## 2. Conclusion

### 2.1. *Morphology of M87 jet and the BZ mechanism*

Our results show a universal property of the resolved Blandford & Znajek (1977) flow with large parallel (to the local magnetic field) momentum of emitting particles: all images are spine-brightened, not edge-brightened as observed. No special prescription for emissivity as function of the flux function parameter $r_0$ can change that: they are all spine-brightened. The assumption of parabolical flux surfaces is, naturally, an analytic approximation, yet the universality of the result - spine-brightened profile - ensures that it will be applicable to more general cases.

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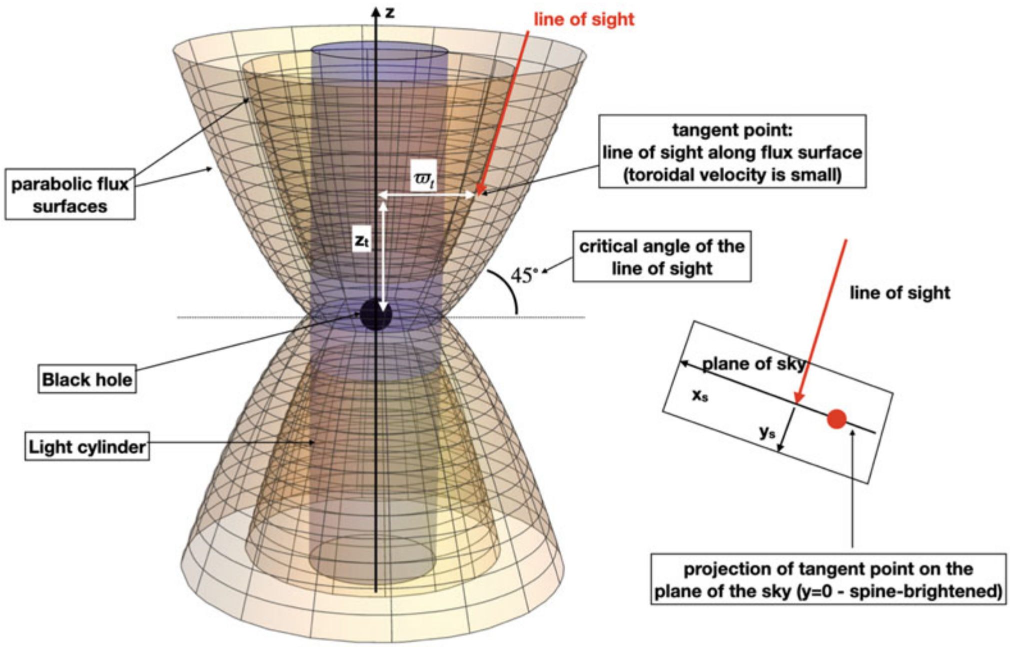


**Figure 3.** 3D rendering of parabolic magnetosphere. The vertical cylinder is the light cylinder. The insert on the right shows the sky image for a particular chosen line of sight. Due to high Doppler boosting the brightness peaks on the $y$ axis - the spine.

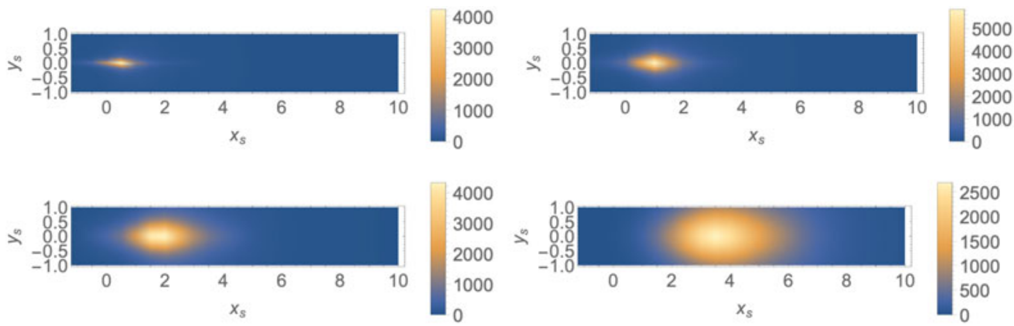


**Figure 4.** Image maps for emission from different magnetic flux surfaces, observer angle $\theta_{ob} = \pi/12$. The axes correspond to projected distances measured in terms of the light cylinder radius. All images are spine-brightened.

We then conclude that Blandford & Znajek (1977) mechanism is not responsible for the M87 jet, at least in its pure form. †

The Blandford & Znajek (1977) mechanism can still be operational - and, e.g. responsible for the bright core in the images of M87 in case of purely radial outflow at small $r$, but it does not drive the observed jet. Another possibility is that the sheath is slowed down by the interaction with the disk corona - while the core remains relativistic, with emission beamed away. This would correspond to emission coming only from innermost flux surfaces, top row in Fig. 4 - it is still spine-brightened, but shows only in the small part of the image.

† By *BZ mechanism* we understand generation of collimated relativistic jet. The relativistic $e^{\pm}$ we describe do extract energy from the spin of the black hole.

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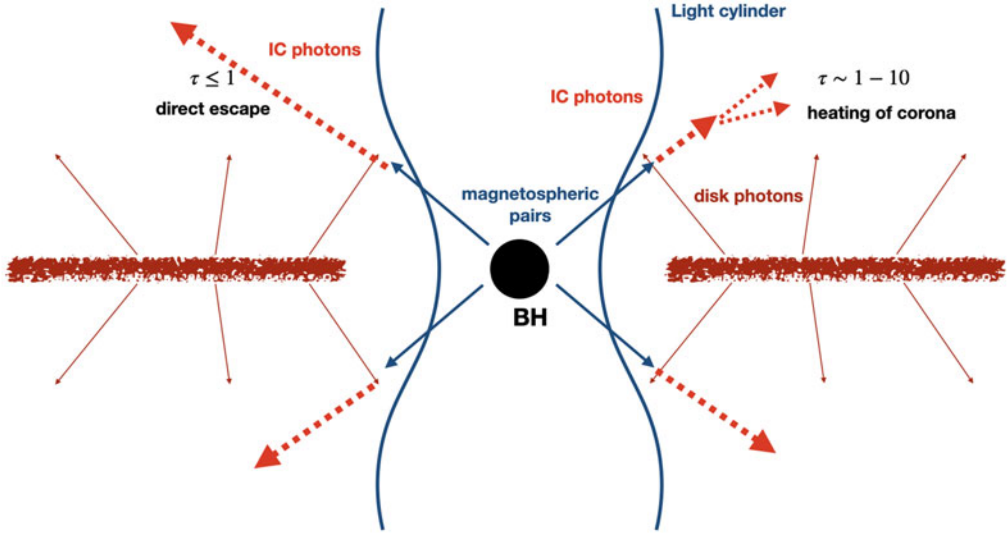


**Figure 5.** Cartoon of the IC emission by accreting black hole. Particles accelerated with the black hole magnetosphere to $\gamma_0 \gg 1$ IC scatter the soft photons from the disk. The resulting signal is (i) quasi-isotropic; (ii) highly variable due to temporal variations of the gap-produced particle flux.

In contrast disk-produced outflows Blandford & Payne (1982) start non-relativistically. The extended structure observed in M87 is thus inconsistent with the magnetosphere-produced jet, but is consistent with the disk-produce jets.

### 2.2. *Blazar-like phenomena from non-aligned ANGe*

The observation of rapidly variable very high energy (VHE) gamma-rays from non-aligned active galactic nuclei e.g., from M87 and Cen A, proves challenging for conventional theoretical acceleration and emission models Aharonian et al. (2006); Acciari et al. (2008); Rieger & Aharonian (2008). Even for the jet-aligned Blazers variations down to a few minutes time scale, smaller than the expected size of the black hole Aharonian et al. (2005), are difficult to explain.

The present model provides a possible answer, Fig. 5: (i) particles are streaming relativistically, radially and quasi-isotropically *right in the vicinity of the black hole*. If the flow varies on time scale $\sim 1/\Omega_{BH}$, then the typical time scale of variability $t_{var}$ is

$$t_{var} \sim (c/\Omega_{BH}) \times 1/\gamma_0^2 = a_{Kerr}^{-1} \times R_{BH}/c \times 1/\gamma_0^2 \tag{2.1}$$

where $a_{Kerr}$ is the Kerr spin parameter and $R_{BH}$ is the horizon size of the black hole. Since the expected Lorentz factor $\gamma_0$ can be in the thousands, the variability time scale cane be very short.

## References

Acciari, et al. 2008, *ApJ*, 679, 397
Aharonian, et al. 2005, *A&A*, 442, 895
Aharonian, et al. 2006, Science, 314, 1424
Bicknell, G. V., & Begelman, M. C. 1996, *ApJ*, 467, 597
Blandford, et al. 2019, *ARAA*, 57, 467
Blandford, R. D., & Payne, D. G. 1982, *MNRAS*, 199, 883
Blandford, R. D., & Znajek, R. L. 1977, *MNRAS*, 179, 433
Kim, 2018, *A&A*, 616, A188
Nakamura, M., & Asada, K. 2013, *ApJ*, 775, 118
Rieger, F. M., & Aharonian, F. A. 2008, *A&A*, 479, L5

https://doi.org/10.1017/S1743921324000334 Published online by Cambridge University Press