MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Charge-starved, Relativistic Jets in Blazars

John G.Kirk and Iwona Mochol

Max-Planck-Institut für Kernphysik, Heidelberg, Germany

Abstract: Very rapid variations of the gamma-ray flux from blazars suggest that there is a mechanism at work which modulates blazar emission on timescales much smaller than the light-crossing time of the black hole's event horizon. We propose a scenario in which blazar photons are modulated at the frequency ω of a large-amplitude wave that is launched in the polar region of the central, rotating black hole, and propagates in a charge-starved jet. Using a two-fluid ($e^{\pm}$) description, we find the outflow exhibits a delayed acceleration phase, that starts when the inertia associated with the wave currents becomes important. The emission of the accelerating jet is observed to be modulated provided that the density of pairs, produced in an electromagnetic cascade, is sufficiently low.

Introduction

H.E.S.S. observations of PKS 2155-304 show remarkably rapid variability on timescale $\sim 2-5$ minutes [1, 4], which is roughly one hundred times smaller than the light crossing time of the gravitational radius $r_{\rm g} = GM/c^2$. In analogy with pulsars, such fluctuations can emerge naturally if the assumption of axisymmetry is abandoned. It seems plausible that a generalised form of the axisymmetric Blandford-Znajek mechanism [3] will cause a non-axisymmetric magnetosphere of a rotating black hole to drive a Poynting-flux-dominated jet, part of which will propagate in the low-density funnel around the rotation axis. In our model [5], the jet emission is assumed to be modulated at the frequency ω of a large-amplitude wave that is launched in the funnel and propagates along with the jet.

Jet parameters

- the strength parameter $a = a_0\,(c/\omega r)$, where
$$a_0 = \left[4\pi e^2 L/\left(m^2 c^5 \Omega_{\rm s}\right)\right]^{1/2} \qquad (1)$$
L is the luminosity in solid angle $\Omega_{\rm s}$
- the mass-loading of the jet $\mu = L/\dot{M}c^2$ or equivalently the pair multiplicity κ - here specified by its value $\kappa_{r_{\rm g}}$ at $r = r_{\rm g}$:
$$\kappa_{r_{\rm g}} \approx \frac{a_0}{4\mu}\left(\frac{c}{\omega r_{\rm g}}\right) \qquad (2)$$
- the magnetisation parameter σ describing the ratio of the energy flux carried by electromagnetic fields to that carried by particles. For particles $e^{\pm}$ of Lorentz factor γ,
$$\sigma = (\mu/\gamma) - 1 \qquad (3)$$
Here we specify its value σ_0 at the "launching" radius, inside of which the ideal MHD approximation is assumed to hold.

Application to blazar variability

If the variation timescale, expressed in units of $100\,$s is $\Delta t_{100} = (2\pi/\omega)/(100\,{\rm s})$, the observables for PKS 2155-304 are given by

$$a_0 = 3.4\times10^{14} L_{46}^{1/2}, \qquad \omega = 0.06\ {\rm s}^{-1}\Delta t_{100}^{-1}$$
$$\rightarrow \mu = 2.7\times10^{11}\Delta t_{100}\kappa_{r_g}^{-1}L_{46}^{1/2}M_9^{-1}$$

The acceleration phase starts at a distance

$$r_{\rm acc} \approx 1.2\,\Delta t_{100}^{1/3}\,\kappa_{r_{\rm g}}^{2/3}\,L_{46}^{1/6}\,M_9^{2/3}\ {\rm pc}$$

The criterion that the modulations of the jet emission are not washed out by the travel time of the signal across the source is

$$\gamma_{\rm w}^2\, 2\pi c/\omega > r \qquad (4)$$

and leads to an upper limit on the multiplicity:

$$\kappa_{r_{\rm g}} < 14\,\Delta t_{100} L_{46}^{1/8} M_9^{-1} \qquad (5)$$

Conclusions

- charge-starved jets accelerate when particle inertia becomes important ($p_\perp \approx 1$) at $\sim r = 1.2\,$pc (non-MHD effect)
- any resulting emission is observed to be modulated if pair loading is not too large ($\kappa_{r_{\rm g}} \lesssim 10$)
- in rapidly variable sources the presence of vacuum gaps is implied

Subluminal waves

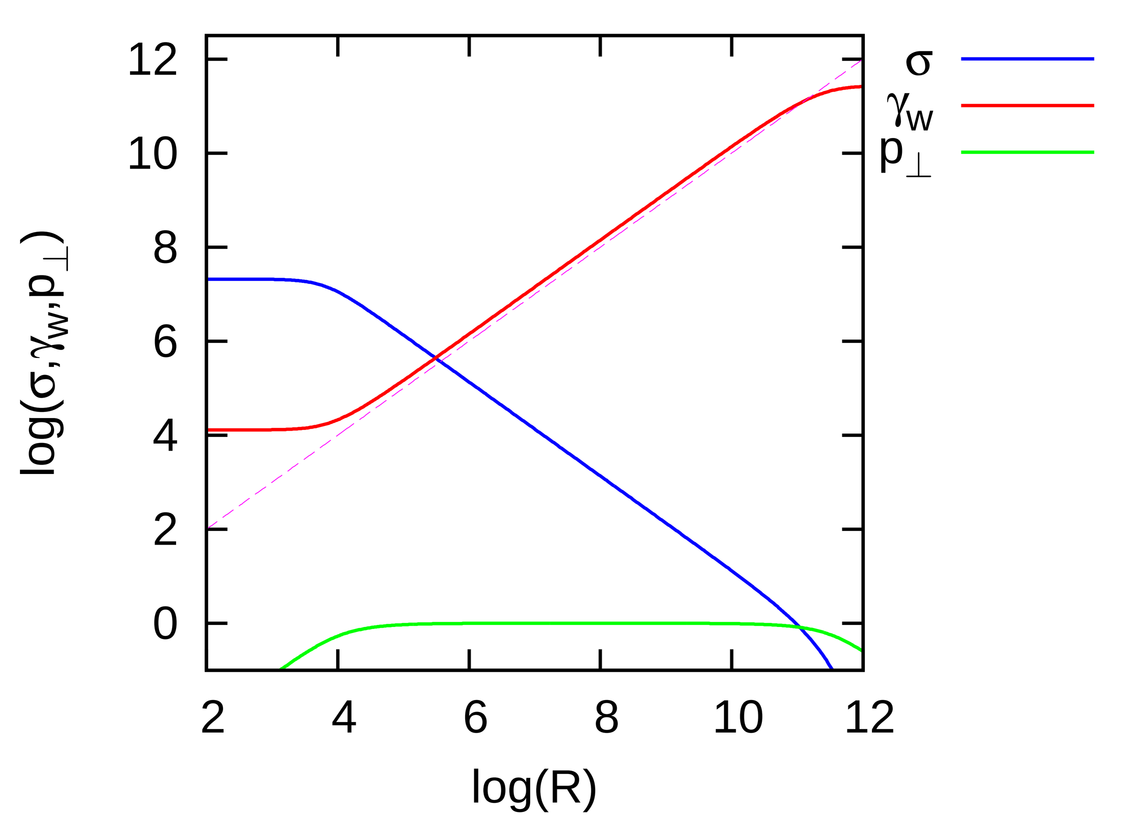
The model:

- plasma density above the poles of a spinning black hole is determined not by accretion, but by the pair production multiplicity κ_{r_g} in the strong electromagnetic fields threading the hole
- resulting outflow is charge-starved and non-ideal MHD effects become important
- the jet is modelled as two cold, ultrarelativistic charged ($e^{\pm}$) fluids. It remains neutral, with the radial momenta $p_{\parallel_+} = p_{\parallel_-}$ and perpendicular ones $p_{\perp_+} = -p_{\perp_-}$ in units of mc
- from the polar regions a circularly polarized transverse wave is launched and propagates radially with a Lorentz factor $\gamma_{\rm w}$
- the system is described by the continuity equation, the equations of motion of the fluids, Faraday's and Ampère's laws
- in the lowest order of the short-wavelength approximation $r \gg c/\omega$ we obtain large-amplitude plane-wave solutions, using the approach introduced by [2].

Subluminal mode:

- particles are in resonance with the wave $\beta_{\rm w} = p_\parallel/\gamma$
- at every point plasma currents are directed along the magnetic field $\boldsymbol{B} \parallel \boldsymbol{p}_\perp$ (force-free shear)
- in the wave frame the electric field vanishes, the magnetic field vector has constant magnitude and rotates through 2π radians over one wavelength.

Figure 1: The solution as a function of the dimensionless radius $R = \mu r\omega/(a_0 c)$, plotted for $a_0 = 3.4\times10^{14}$, $\mu = 2.7\times10^{11}$, $\sigma_0 = \mu^{2/3} = 4.2\times10^7$, together with the approximation $\gamma_{\rm w} = R$.



The first order solution reveals the radial evolution of the jet in three phases:

1. coasting (MHD) $R \ll \mu/\sigma_0$: inertia of current carriers negligible $p_\perp \ll 1$, supersonic, relativistic, radial MHD flow
$$\gamma \approx \gamma_{\rm w} \approx \mu/\sigma_0, \quad \sigma = \sigma_0 \lesssim \mu^{2/3}$$
2. acceleration $\mu/\sigma_0 \ll R \ll \mu$: inertia associated with the current contributes to the energy-momentum flux $p_\perp \approx 1$
$$\gamma \approx 2R, \quad \gamma_{\rm w} \approx \sqrt{2}R, \quad \sigma \approx \mu/(2R)$$
3. free-streaming $R \gg \mu$: E-M fields negligible $\sigma \ll 1$
$$\gamma \approx \gamma_{\rm w} \approx \mu, \quad |p_\perp| \ll 1$$

References

[1] F. Aharonian et al. 2007, ApJ, 664, L71
[2] A.I. Akhiezer and R.V. Polovin 1956, Sov. Phys. JETP, 3, 696
[3] R. D. Blandford & R. L. Znajek 1977, MNRAS, 179, 433
[4] HESS Collaboration, A. Abramowski et al. 2010, arXiv:1005.3702
[5] J. G. Kirk & I. Mochol 2011, ApJ, 729, 104

MAX-PLANCK-GESELLSCHAFT