Variability properties of jets from accreting black holes using GRMHD simulations

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Introduction

- Relativistic jets are a common phenomena in accreting black hole (BH) systems.
- They are observed for different mass scale of BH; from stellar mass BH (~10 $M_{\odot}$, eg. in BH X-ray binaries and gamma ray bursts, GRBs); to supermassive BH (10^5 -10^{10} $M_{\odot}$, in active galaxy nuclei, AGNs).
- GRBs are among the most energetic events in the universe releasing a total energy of 10^{52} -10^{54} erg.
- Blazars are a type of AGNs characterized by a non-thermal radiation produced in a relativistic jet pointing towards our line of sight.
- There are similarities in launching and collimation mechanisms of these sources.
- These jets are Poynting-dominated, and powered by the Blandford-Znajek mechanism which can extract energy from a rotating black hole

$$P_{Bz} \sim \frac{\phi_{BH}^2 \cdot \Omega_{BH}^2}{c}$$

- Various observations of the emitted jets from BH sources show variability.

Observed correlations

- Despite the central object mass difference, it may be possible that blazars and GRBs are sharing similar jet physics.
- Wu et al. (2016) showed that, Blazars and gamma ray bursts share some properties of their jets, despite different Lorentz factors and accreting black hole masses.
- It is found by them that the anti-correlation between minimum variability time-scale (MTS) and Lorentz factor, Γ, as found only in GRBs by Sonbas et al. (2015) can be extended to blazars as well
- Motivated by these observations, we numerically investigated the correlations using GRMHD simulations

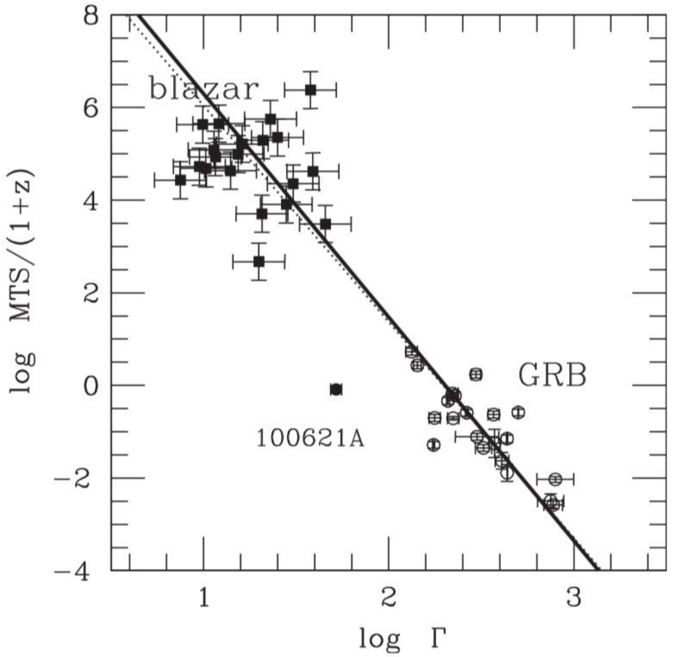

Fig.1: The MTS versus Lorentz factor, Γ, for GRBs and blazars. The solid line represents the best linear fit for 21 GRB. The dotted line represents the best fit for GRBs (excluding GRB100621A) and blazars in their sample. They find a joint correlation of a joint correlation of MTS $\propto \Gamma^{-4.7\pm0.3}$ Credit: Wu et al., 2016.

Numerical setup

- We explore the scenario of magnetically driven accretion and jet variability related to the Magnetorotational Instability (MRI) timescale.
- We use the modified version of the HARM code (High Accuracy Relativistic Magnetohydrodynamics), a conservative, shock capturing scheme, for evolving the equations of GRMHD, developed by Gammie et al. (2003).
- Our initial condition assumes the existence of a pressure equilibrium torus, embedded in a poloidal magnetic field.
- The torus initial configuration is the Chakrabarti (1985) accretion disk model. Here, the angular momentum distribution has a power law relation
- The inner edge of the torus is $r_{in} = 6\ r_g$, and the position of the maximum pressure is $r_{max} = 16.5\ r_g$.

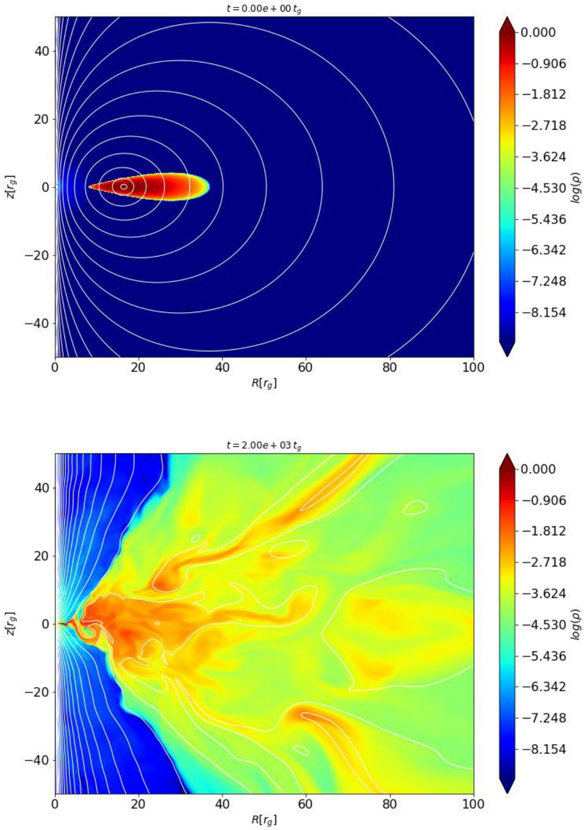

Fig.2: Initial conditions and evolved state. Torus density structure and magnetic field contour lines at time t=0 and at time t=2000 M for the model with β_{max} =60 and Kerr parameter a = 0.99

Numerical setup

- We implement the magnetic field as the magnetic field produced by a circular current inside the torus
- We express the only non-zero component of the vector potential as (Jackson, 1999):

$$A_\phi(r,\theta) = A_0 \frac{(2 - k^2)K(k^2) - 2E(k^2)}{k\sqrt{4Rr\sin\theta}}, \quad k = \sqrt{\frac{4Rr\sin\theta}{r^2 + R^2 + 2rR\sin\theta}}$$

- with E and K the complete elliptic integrals, R the position of the circular current in the torus (same as r_{max} in our models) and A_0 a parameter used to scale the magnetic field.
- The code works in GR framework. For a convenient aspect, dimensionless units are adopted, with G=c=M= 1. This means that the mass of the black hole will scale the simulation.
- All simulations start with this initial configuration and evolve with a jet launching

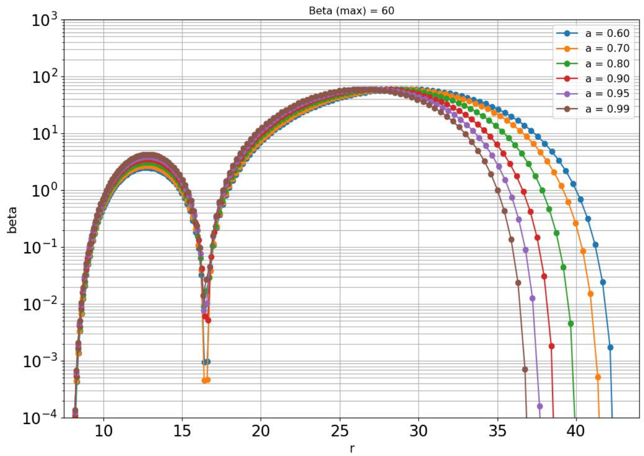

Fig.3: Initial distribution of gas to magnetic pressure ratio, β, in the torus at time t=0 for the model with normalization β_{max}= 60

- The models are parameterized with the black hole spin, and the initial magnetization of the matter.
- We use the initial gas to magnetic pressure ratio, $\beta = p_{gas} / p_{mag}$, across the torus, to scale the magnetic field

Jet properties and central engine

- We use the energetic parameter $\mu = -T^r_{\ t} / \rho u^r$, to study the variability of the jet emission (where $T^r_{\ t}$ is the energy component of the energy- momentum tensor, ρ is the gas density, and u^r is the radial velocity). Assuming a flat spacetime, we can interpret this parameter as the total plasma energy flux normalized to the mass flux (Sapountzis and Janiuk, 2019)
- It can also provide an estimate of the maximum achievable Lorentz factor $\Gamma_\infty = \mu$, assuming that the Poynting and the thermal energy is transformed to baryon bulk kinetic (Vlahakis and Königl, 2003; Sapountzis and Janiuk, 2019).
- We calculate the μ at two chosen points along the jet direction located at $r = 150\ r_g$, $\theta = 5^o$ and $\theta = 10^o$ and we take the average value.
- The Lorentz factor is calculated as the average of μ in time, $\Gamma = \langle \mu \rangle_t$. This will be in units of M.
- Minimum variability Time Scale (MTS) ~ peak widths at their half maximum on the μ – t plot

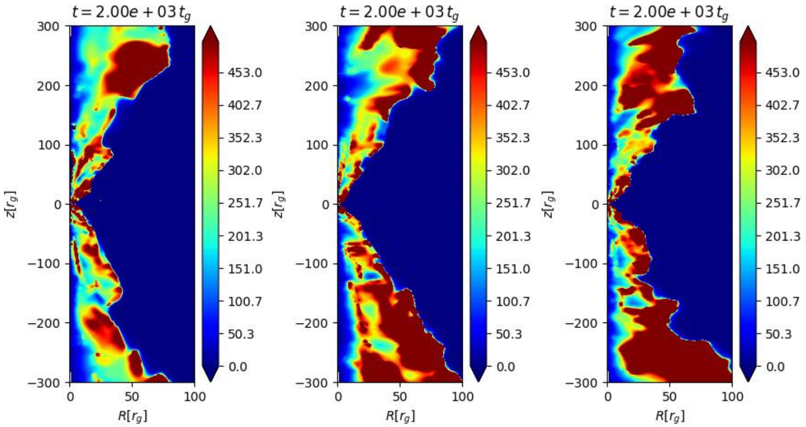

Fig.4: Jet structure at time t=2000 M. Plot shows distribution μ for models with $\beta_{max} = 600$; Models display jets launched from spinning black holes with the Kerr parameter, a = 0.6 (left), a = 0.8 (middle), and a = 0.95 (right).

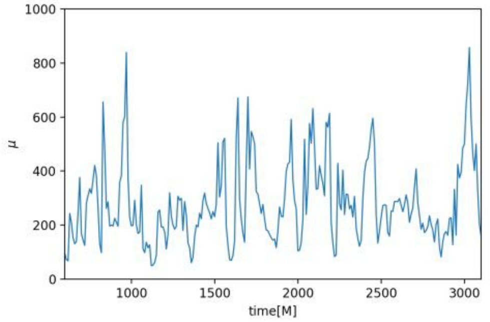

Fig.5: Variability of jet energy parameter μ as function of time, for the model with $\beta_{max} = 600$ and Kerr parameter a = 0.95

Discussion and conclusions

- The variability of the jet, studied in terms of the pulses duration, is driven by the magneto-rotational instability in the disk.
- We notice highly inhomogeneous outflows, where larger values of μ are reached at the edges of the jets rather than at the z polar axis.
- We qualitatively study the jet profile, as function of polar angle, at a large distance (~2000 r_g) from the central engine. It shows that the most energetic part of the jet is located inside a narrow region of $\theta < 15^o$

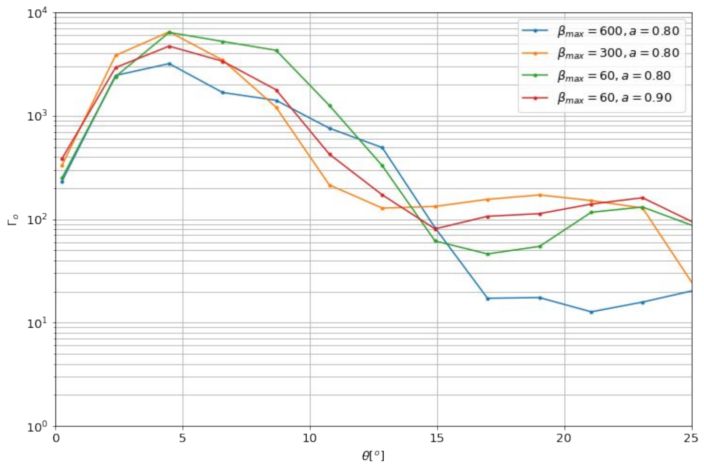

Fig. : Time averaged jet Lorentz factor as a function of polar angle, measured at distance of 2000 r_g.

Discussion and conclusions

- We studied three family of models with varying strength of magnetization (with maximum gas to magnetic pressure inside the torus 60, 300 and 600).
- We also study models with Kerr parameter ranging from 0.99 to 0.6 within each above family of models
- There is an anti-correlation found between the calculated MTS, and the black hole spin parameter of the central engine.
- The latter is directly responsible for the jet launching via the Blandford-Znajek process, so that the jet Lorentz factor will increase with the black hole spin, while the MTS decreases with it.
- The correlations for the inferred minimum variability timescale and jet Lorentz factor is confirmed in our models.

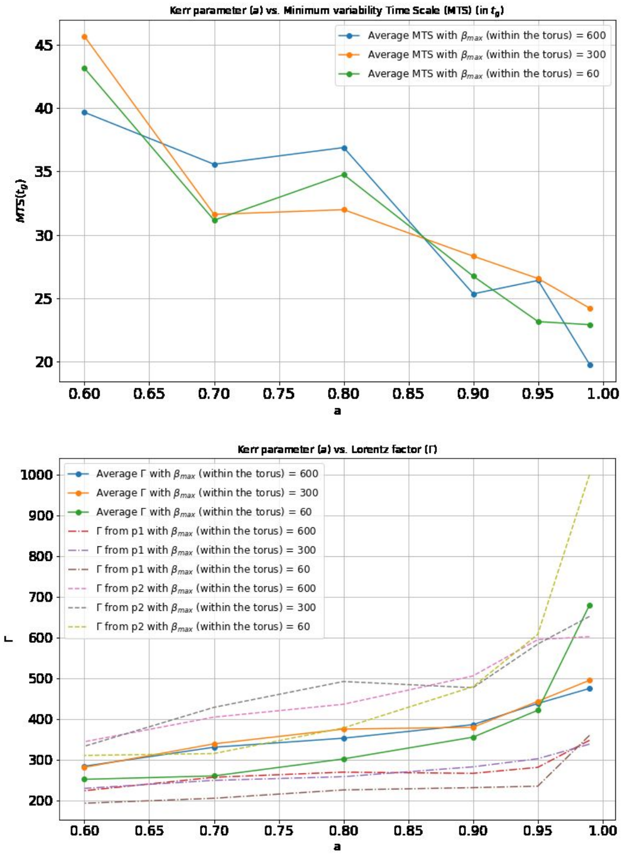

Fig.6: Correlations between (a) the Kerr parameter a and Minimum variability Time Scale (MTS) and (b) the Kerr parameter a and Lorentz factor Γ from our models.

References and Acknowledgements

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