Investigating intra-day variability in the relativistic jets of AGN due to blob propagation using RMHD simluations

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Abstract:

Active Galactic Nuclei (AGN) are compact regions in the centre of galaxies exhibiting higher than normal luminosity. Blazars, the most luminous type of AGN, have relativistic jets that are directed very nearly along the line-of-sight and exhibit variability in their light curves. Observations of intra-day variability for AGN suggest the presence of blobs in their jets. Blob formation has been attributed to shocks, perturbations, and plasmoids generated by magnetic confinement. We investigate the morphology and dynamics of blobs generated with different characteristics (velocity, density, and magnetic fields) and how this can result in variable light curves. Relativistic magnetohydrodynamics (RMHD) jets were simulated using PLUTO, an astrophysical fluid simulation software, and allowed to develop in time forming multiple recollimation shocks. Quasi-spherical blobs were then injected into the jet by varying parameters at the jet base and allowed to propagate and interact with the jet and its shocks. A post-processing code was used to find the integrated specific intensity of synchrotron emission in the radio regime, accounting for relativistic effects. From this, light curves have shown how the specific intensity changed over time and indicated significant variability during blob propagation with peaks that formed during blob-recollimation shock interactions.

1. Introduction:

AGN have been observed to show multi-wavelength variability on time scales of minutes to years. Such events have been attributed to blob propagation within the relativistic jets of AGN with observations noted for radio galaxies in [1] and blazars in [2]. Models describing the formation and subsequent propagation of blobs along the jet column vary from the leptonic blob-in-jet model [3] to compact magnetized blobs produced by red giants that cross the jet close to the central black hole [4].

To understand the observed variability, astrophysical fluid dynamical simulations have previously been tested by injecting shocks, perturbations, and blobs into the jet nozzle (e.g. [5]). RMHD simulations allow the evolution of jet properties such as shocks, turbulence, and magnetic fields to be investigated. A post-processing approximation of the synchrotron emission can be used to calculate the emission and absorption, generating radio maps and light curves, which can be compared to observational data.

2. Jet and blob simulations & emission modelling:

A 3D jet model was constructed in PLUTO Ver 4.3 consisting of 192 x 768 x 192 grid cells with a resolution of 4 grid cells/unit length. Buffer zones were employed on the axes perpendicular to the jet flow and had 24 grid cells on each side with a resolution of 1 grid cell/unit length. An under-dense and thermally pressure matched jet model was used where the ambient medium was initialized and the jet was allowed to propagate from the boundary nozzle. The nozzle was generated by a jet-ambient profile using a normalized modified Gumbel distribution. A force-free magnetic field setup was utilized as found in [6] where the poloidal and toroidal components of the magnetic field are given respectively by,

$$B_z = \frac{B_0}{1+(r/a)^2} \quad (1) \qquad B_\phi = \frac{(r/a)B_0}{1+(r/a)^2} \quad (2)$$

where B_0 parametrizes the magnetic field amplitude, r is the distance from the jet centre, and a is the characteristic radius of the column. The environment was set up in Cartesian coordinates and evolved with time using a linear interpolation method, Hancock time stepping, and the HLLD Riemann solver. A list of parameters for the the jet setup can be found on Table 1.

Blobs were formed by altering a single jet parameter (density, velocity, magnetic field) at the jet nozzle and injected such that the blob evolved based on a quasi-spherical radius profile. A list of parameters for the different blob setups can be found on Table 2.

A post-processing code similar to [7] was used to find the integrated synchrotron intensity. It was assumed the jet contained a uniform distribution of protons and electrons, a certain fraction of the thermal energy was in the power-law distribution of electrons, and that all electrons followed a pure power-law. The normalization constant was applied from [8] with the single power law given by,

$$n(\gamma) = n_0\,\gamma^{-p}, \quad (3)$$

where $n(\gamma)$ is the electron spectrum, γ is the Lorentz factor, p is the spectral index and n_0 the normalization constant. The emission and absorption coefficient approximations were used from [9] and were integrated along the line-of-sight taking into consideration relativistic effects such as Doppler boosting and employing the perpendicular component of the magnetic field to the line-of-sight.

3. Results:

Initially the jet is injected at the base of the computational domain and the simulation is allowed to evolve until the contact discontinuity reaches the top boundary. At this point a blob was injected at the jet nozzle, by changing the magnetic field, velocity or density at the nozzle. Figure 1 displays each blob type after its first interaction with a recollimation shock. Figure 2 shows the integrated synchrotron intensities over the simulation domain from the time of the blob injection until it reached the top boundary of the simulation. The synchrotron emission was calculated at an observed frequency of ν=15x10^9 Hz, assuming an electron index p=2.1, $\gamma_{max}/\gamma_{min}$ =10^7, and a viewing angle θ=0° relative to the jet. The synchrotron intensities were converted from the co-moving reference frame to the observer's frame. Due to the short length scale of the jet (1 computational unit length = 10^{14} cm), the light-crossing time correction was not included.

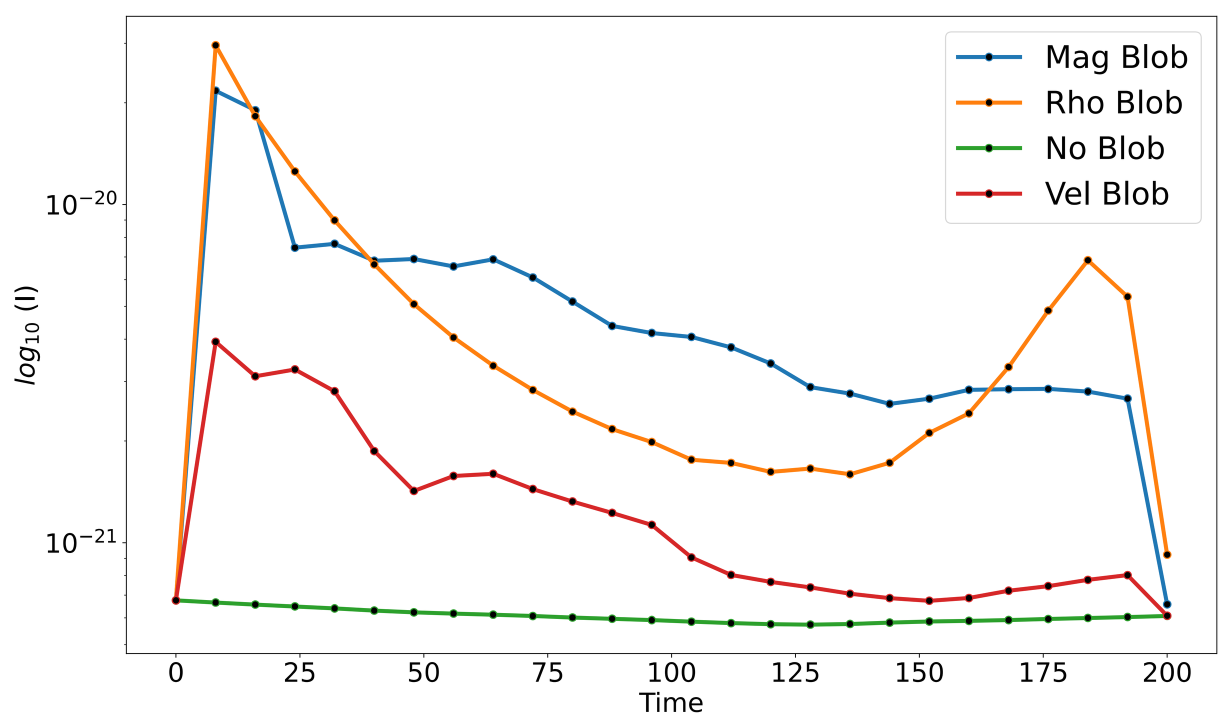

Figure 2: Light curves of the synchrotron intensity in the observer's frame during blob injections with both axes given in arbitrary units. Local peaks formed during blob-recollimation shock interactions.

Table 1: Simulation parameters

Parameters	Value
Jet Lorentz factor (Γ_j)	10
Mach number (M)	8
Density ratio (η)	10^{-3}
Jet density (ρ_j)	1
Magnetic field amplitude (B_0)	0.3
Adiabatic index (γ_{ad})	5/3
Jet, blob, & characteristic radii (r_j, r_b, a)	2, 1, 0.5

Table 2: Blob parameters

Blob type	Value
Density	$10^5\rho_j$
Velocity	$10\Gamma_j$
Magnetic	$50B_{0,j}$

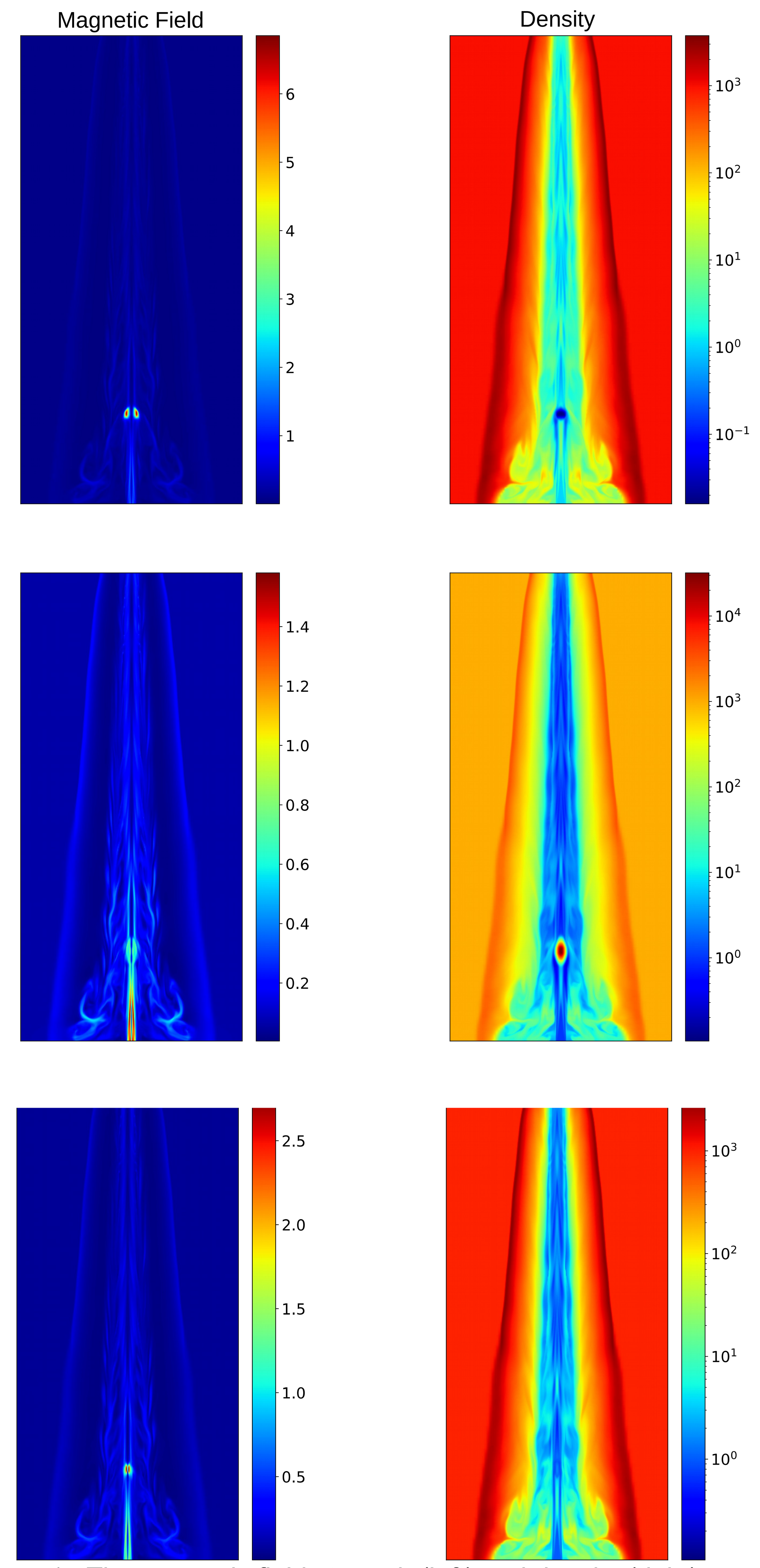

Figure 1: The magnetic field strength (left) and density (right) distributions of the RMHD simulations for magnetic (top), density (middle), and velocity(bottom) blobs. The magnetic field strength and density are given in arbitrary units

4.Discussion and Conclusion:

RMHD simulations of AGN jets were simulated and three different blob types were injected and allowed to propagate. Each type exhibited its own unique light curve showing an increase in the emission from the "No Blob" run. The variability shows local maxima at times ~25, 70, and 155, when the blobs interacted with the recollimation shocks. Strong outflowing shocks developed for each blob type that further propagated into the jet's cocoon region and interacted with the backflow. Future research will look at increasing the simulation's resolution as well as adding more recollimation shocks for the blobs to interact with.

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