Towards Observational Astronomy of Jets in Active Galaxies from GRMHD Simulations

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Abstract - We carry out the process of "observing" simulations of active galactic nuclei with radio jets (hereafter called jet/accretion disk/black hole (JAB) systems) from ray tracing between image plane and source to convolving the resulting images with a point spread function. Images are generated at arbitrary observer angle relative to the black hole spin axis by implementing spatial and temporal interpolation of conserved magnetohydrodynamic flow quantities from a time series of output datablocks from fully general relativistic 3D simulations. We also describe the evolution of simulations of JAB systems' dynamical and kinematic variables, e.g., velocity shear and momentum density, respectively, and the variation of these variables with respect to observer polar and azimuthal angles. We produce fixed observer time intensity maps using various plasma physics motivated prescriptions for the emissivity function of physical quantities from the simulation output, and analyze the corresponding light curves. Our hypothesis is that this approach reproduces observed features of JAB systems such as superluminal bulk flow projections and quasi-periodic oscillations in the light curves more closely than extant stylized analytical models, e.g., cannonball bulk flows. Moreover, our development of user-friendly, versatile C++ routines for processing images of state-of-the-art simulations of JAB systems may afford greater flexibility for observing a wide range of sources from high power BL-Lacs to low power quasars (possibly with the same simulation) without requiring years of observation using multiple telescopes. Advantages of observing simulations instead of observing astrophysical sources directly include: the absence of a diffraction limit, panoramic views of the same object and the ability to freely track features. Light travel time effects become significant for high Lorentz factor and small angles between observer direction and incident light rays; this regime is relevant for the study of AGN blazars in JAB simulations.

Simulations

MODELING PLASMA ACCRETION ONTO KERR BLACK HOLE

- Numerically solve general relativistic magnetohydrodynamic (GRMHD) equations

$$(\rho u^\mu)_{;\mu} = 0$$
$$(T^\mu_\nu)_{;\mu} - G_\nu = 0$$
$$(R^\mu_\nu)_{;\mu} + G_\nu = 0$$

$$T^\mu_\nu = (\rho + u_g + p_g + b^2)u^\mu u_\nu + (p_g + (1/2)b^2)\delta^\mu_\nu - b^\mu b_\nu$$

a few hundred gravitational radii $r_g = GM_{BH}/c^2$ from the black hole

HOSTING AND MANIPULATING DATA

- Store 1.5Tb of simulation datablocks in a directory on KIPAC remote host along with C++ routines for ray tracing by solving radiative transfer equation

to find the intensity on the observer plane

ANALYZING SIMULATION OUTPUT

- Plotting simulation [1] output dynamic and kinematic variables may give insight into processes important in jet emission

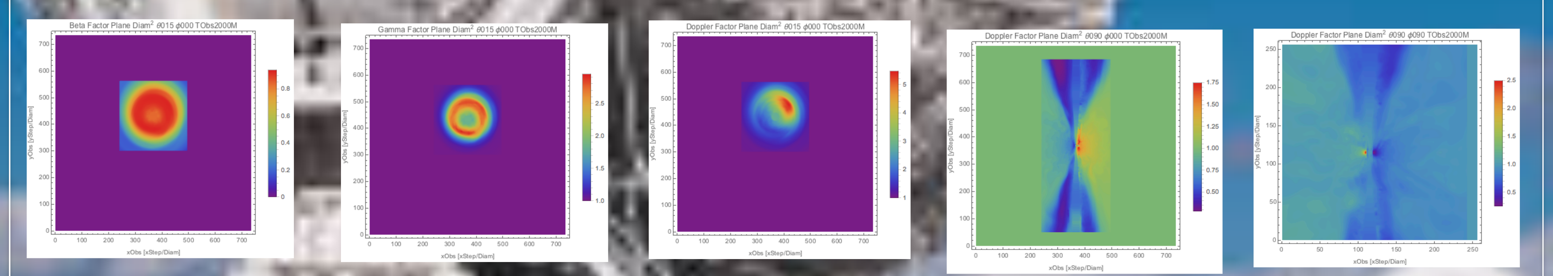


Figure 1. Plots of (left to right) 1.) bulk flow speed parameter β, 2.) Lorentz factor Γ and 3.) Doppler factor viewed from polar angle θ = 15° and azimuthal angle ϕ = 0° on planes 75M (in units where r_g = M) from the center of simulation region and of 4.) and 5.) Doppler factor viewed from (θ , ϕ) = (90° , 0°) and (90° , 90°) on midplanes of the simulation region.

Pipeline

FILE READING ROUTINE

- Reads into remote host simulation binary data files fieldline*.cart.bin.boxzh100.box256x256x256.out20.modelrunlocaldipole3dfiducial
- Maps observer times tObs to simulation spacetime regions contributing emission to an observer plane at constant observer time, removing the middle 2*HPillboxOn2/HSim of the vertical simulation range to suppress disk emission

INTERPOLATION ROUTINE

- Linearly interpolates physical quantities on 3D Cartesian lattice

INTEGRATION ROUTINE

- Computes emission (from a list of emissivities j) from a plane normal to any observer direction (n(θ,ϕ))
- Integrates emission from planes normal to the observer direction

IMPLEMENTATION

- The parameters tObs,θ,ϕ,HPillboxOn2/HSim, j, fieldline*.cart.bin.boxzh100.box256x256x256.out20.modelrunlocaldipole3dfiducial are input at the command line at runtime
- Use routines to make movies of jets at various angles using various emissivity prescriptions and disk masking, as shown in the intensity maps below

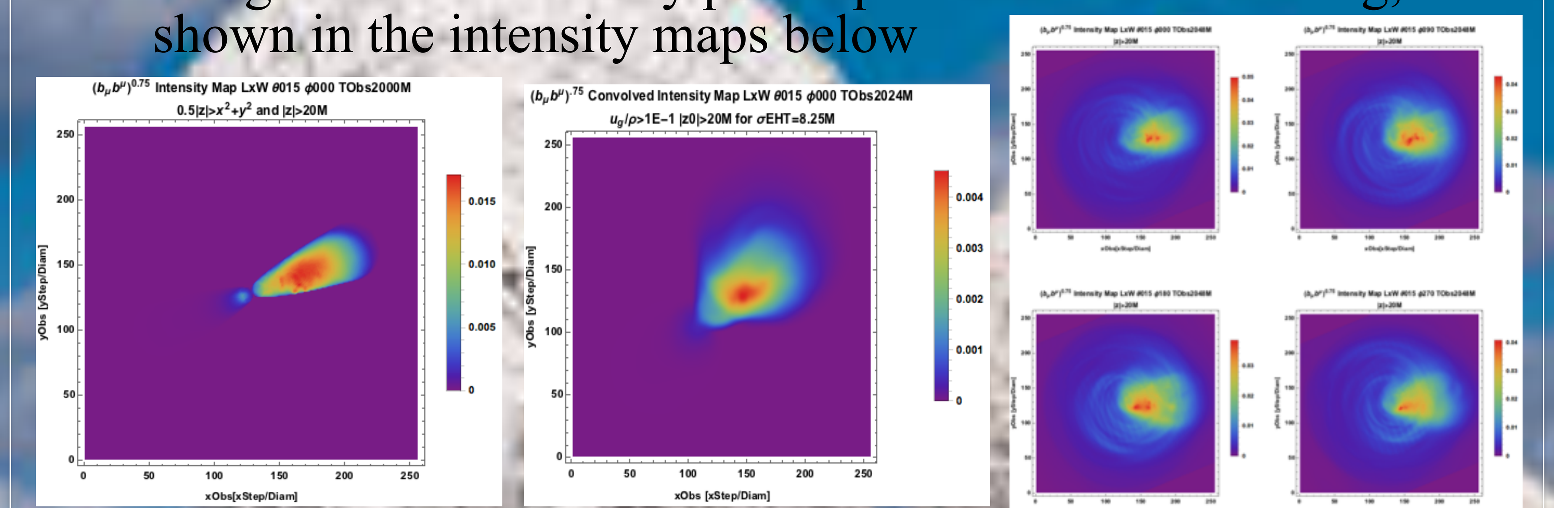
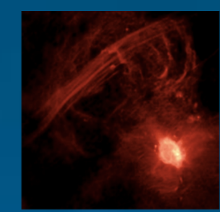


Figure 2. Intensity maps of synchrotron model emissivity $j \sim u_g(b_\mu b^\mu)^{(1+\alpha)/2}$ (where u_g and α=0.5 are the lepton gas energy density and spectral index, respectively) with (left to right) 1.) parabolic geometric subtraction of regions away from $|z|>x^2+y^2>20$ at observer time t_{Obs}=2000M viewed from observer orientation (θ , ϕ) = (15° , 0°), 2.) the same emissivity and orientation now at t_{Obs}=2024M convolved with a Gaussian beam (σ=8.25M) with masking of $u_g/\rho<0.1$ and the disk region in the middle 20% of the simulation, and 3a-d.) (from top left to bottom right) the same emissivity and observer polar angle now viewed at 2048M with observer azimuthal angles ϕ = 0°,90°, 180° and 270°, respectively, and disk subtraction setting to zero regions away from $x^2+y^2>20$.

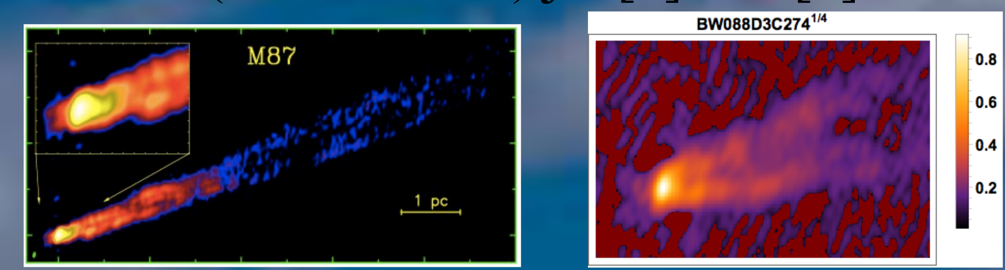
Observations

VERY LONG BASELINE RADIO OBSERVATIONS

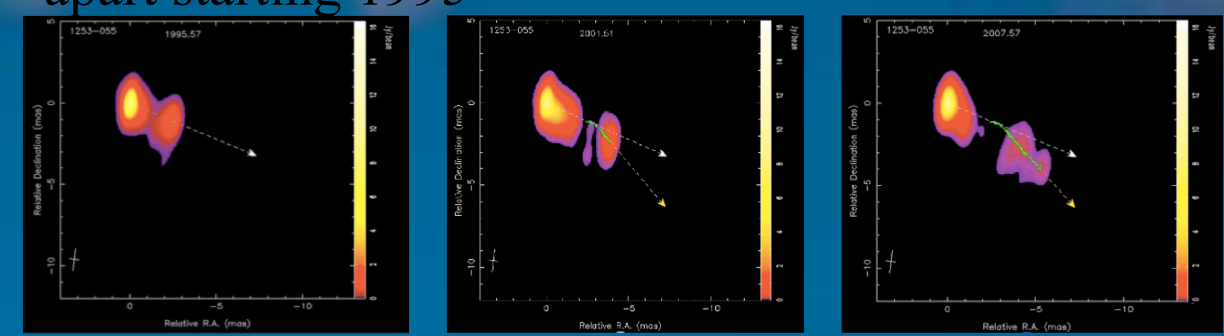
- Radio core of Sgr A* at galactic center [2] 8.0×10^3pc (26×10^3ly) away



- Messier 87 (M87/3C 274) jet [3] and [4]



- Quasar 3C 279 (z = 0.536) [5] with frames 6 years apart starting 1995



- The Event Horizon Telescope is a next generation sub-mm wavelength very long baseline array (such as the VLBA depicted in poster background) promising to resolve event horizon scale features around the black holes in Sgr A* and M87

References
1) McKinney, J. C. and Blandford, R. D., Stability of Relativistic Jets from Rotating, Accreting Black Holes via Fully Three Dimensional Magnetohydrodynamic Simulations, Mon. Not. R. Astron. Soc. **000**, I-6 (2009), arXiv:0812.1060v2 [astro-ph.HE].
2) XRT-C, (2014), Our View to the Centre of the Galaxy, retrieved Apr. 13, 2015 from http://www.xrt-s.co.uk/2014/03/.
3) Gilster, P., (2007), M87's Jet (and Memories of Clarke), retrieved Apr. 14, 2015 from http://www.centauri-dreams.org/?p=1518.
4) Walker, R. C., (2015), personal correspondence.
5) Lister, M., MOJAVE Collaboration, (2010), retrieved Apr. 14, 2015 from The Central Engines that Power Active Galaxies PowerPoint presentation by Tony Readhead.