THREE-DIMENSIONAL RELATIVISTIC JET SIMULATIONS OF RADIO-LOUD ACTIVE GALACTIC NUCLEI (AGN)

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ABSTRACT

We have computed a suite of simulations of propagating three-dimensional relativistic jets, involving substantial ranges of initial jet Lorentz factors and ratios of jet density to external medium density. These allow us to categorize the respective AGN into Fanaroff-Riley class I (jet dominated) and FR class II (lobe-dominated) based upon the stability and morphology of the simulations. We used the Athena code to produce a substantial collection of large 3D variations of jets, many of which propagate stably and quickly for over 100 jet radii, but others of which eventually go unstable and fill up slowing advancing lobes. Comparing the times when some jets go unstable to these initial parameters allow us to find a threshold where radio-loud AGNs transition from class II to class I. With these high resolution fully 3D relativistic simulations we can represent the jets more accurately and thus improve upon and refine earlier results that were based on 2D simulations.

INTRODUCTION

Active galactic nuclei (AGN) are galaxies that not only have a supermassive black hole at the center, but also emit an intense amount of radiation due to solely the black hole and not the surrounding stars within the galaxy. The black hole is so large and in the process of consuming so much matter, it causes the material it has not yet swallowed to generate so much energy and heat that compared to all the light produced from the hundreds of thousands of stars in the respective galaxy, we only see the radiation due to the black hole! A small percentage of these AGN, around 10 percent, are classified as radio-loud (e.g. Jiang et al. 2007), primarily meaning that they are characterized by relativistic plasma jets extending from the north and/or south poles of the black hole. These jets are linear structures that transport energy and particles at speeds near the speed of light from the compact central region of the AGN out to thousands of parsecs or sometimes even millions of parsecs in length. Another important characteristic of these jet structures is that they emit synchrotron radiation, an observational phenomenon where charged particles such as electrons spiral around magnetic fields causing yet again large amounts of radiation across the electromagnetic spectrum to be emitted (Urry & Padovani 1995). Due to the uniqueness and high-energy of these radio-loud AGN we desire to understand the underlining physics of them.

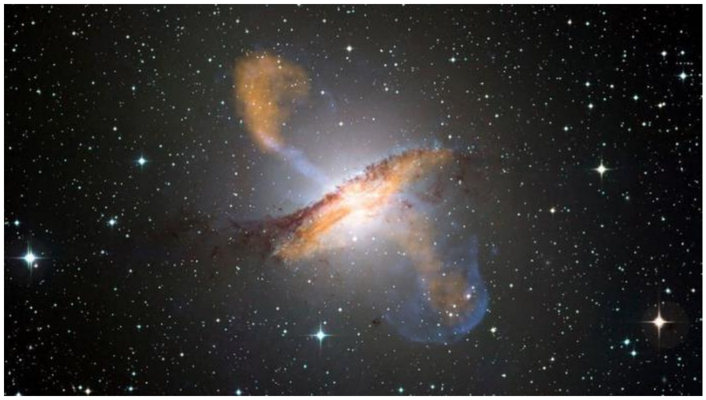

Figure 1: An example of an AGN, in particular Centaurus A. In the Image, the galaxy disk is in the visible spectrum and the jets are in the radio spectrum.

FR I and FR II

The previously described radio jets have long been classified into two categories (Fanaroff & Riley 1974) based upon their radio morphology. Fanaroff-Riley I (FR I) sources have jet-dominated emission, with the majority of their radiation arising from the inner halves and are weaker. The FR II on the other hand, or classical double sources, have emission dominated by lobes containing terminal hot-spots. Furthermore, some hybrid-morphology radio sources (HYMORS) have been discovered that show FR I structure on one side of the radio source and FR II morphology on the other (Gopal-Krishna & Wiita 2000). These sources are important in understanding the basic origin of the FR I and FR II dichotomy, where the different morphologies may be induced by intrinsically different jet properties, interactions with different environments on either side of the source, or long-term temporal variations combined with the time-lag in the observer's frame between evolving approaching and receding lobes.

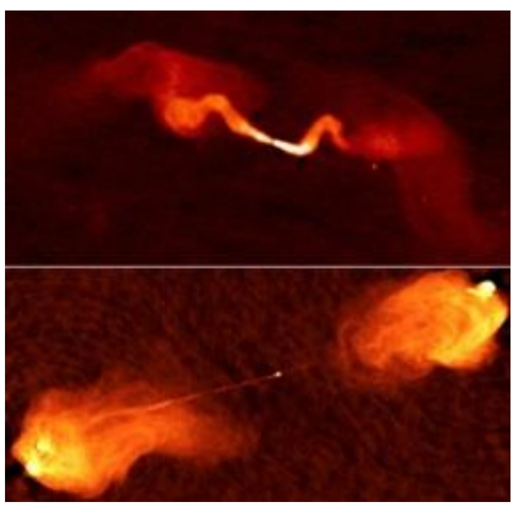

Figure 2: Two radio galaxies with jets seen using a radiograph. (top) An example of a FR I type AGN, in particular radio galaxy 3C 31. Notice how the jets are most luminous in the inner half and they become unstable when they reach a certain point. Image courtesy of the NRAO/AUI. (bottom) An example of a FR II type AGN, in particular Cygnus A. In this case the jets are most luminous at the out lobes and they remain stable. Image courtesy of the VLA.

METHOD OF RESEARCH

FR I type or FR II type, these radio-loud AGN are impossible to physically create here on Earth so like most astrophysical research in order to study the astronomical objects we computationally model them using supercomputers. Because the jets are comprised of plasma, we can effectively treat them as a fluid and thus we employ hydrodynamical computer codes to generate our models. These hydrodynamical simulations of propagating jets are of critical importance to the understanding of radio galaxies and now have a history spanning four decades (Rayburn 1977; Wiita 1978; Norman et al. 1982). These simulations give fundamental support to the idea of the twin-jet models for radio galaxies dating to Scheuer (1974) and Blandford & Rees (1974). Like most computational work, the complexity of the simulations has increased in parallel with growing computational power and algorithm development, leading to better understanding of the jet phenomenon, focusing on the study of the morphology, dynamics and non-linear stability of jets at kilo-parsec and larger scales.

To perform our specific research here at TCNJ we use the college's ELSA High-Performance Computing (HPC) cluster in parallel with the Athena code developed by J. Stone and colleagues (Gardiner & Stone 2005; Stone et al. 2008; Beckwith & Stone 2011). It is a highly efficient, grid-based, code for astrophysical magnetohydrodynamics (MHD) that was developed primarily for studies of the interstellar medium, star formation, and accretion flows. Athena has the capability to include special relativistic hydrodynamics (RHD) and MHD, static (fixed) mesh refinement and parallelization. The discretization is based on cell-centered volume averages for mass, momentum, and energy, and face-centered area averages for the magnetic field. In order to solve a series of partial differential equations expressing conservation laws, the rest density, pressure, velocity, internal energy, and magnetic field are calculated though in these RHD simulations the magnetic field was set to zero.

With the goal to understand the physics and characteristics of FR I type jets and FR II type jets, we have simulated these propagating jets and created a very extensive suite of both medium-power and high-power jets in three-dimensions. Much previous work has been devoted to modeling relativistic jets in two-dimensions (e.g. Pollack et al. 2016) rather than three-dimensions due to a lack of computational power, so after a thorough literature search, to our knowledge we are among the first research groups to model these large-scale jets three-dimensionally while maintaining high-resolution. Since in reality the jets are three-dimensional this enhancement allows us to classify them more accurately, make better predictions concerning the jets, and develop a stronger understanding of them.

SIMULATIONS

We use the Athena code for special relativistic hydrodynamics to produce 3D simulations of jets propagating through initially uniform external, or ambient, media, with wide ranges of powers. To model a hydrodynamic jet, the initial physical parameters of jet velocity, v_j (assumed constant across the cross-section for our initially cylindrical jets), proper ambient and jet densities (ρ_a and ρ_j , respectively), ambient and jet pressures (P_a and P_j) and adiabatic index, Γ, must be specified. Of these, the dominant variables are v_j and $\eta = \rho_j/\rho_a$ and these are the ones we will discuss. With substantial experimentation involving different code parameters, our best overall results for faster jets came from simulations of higher resolution 3D RHD jets with $1200 \times 500 \times 500$ zones with the length along the axis extending to 120 jet radii, and on $600 \times 500 \times 500$ for grids extending only out to 60 jet radii. With research still on-going, upwards of 60 RHD simulations have now successfully been performed with the Athena code with different combinations of jet velocities (v_j) and jet-to-ambient matter density ratios (η). The simulations contain a range of η from 0.0005 to 0.0316 and a range of initial v_j from 0.7c to 0.995c. A summary of the results of these simulations are shown in Figure 3. The circles in the figure represent runs with jets that eventually go unstable before the end of the grid at 60 or 120 jet radii is reached and can be considered to correspond to FR I radio sources if scaled to extragalactic dimensions. Triangles show parameters of runs with jets that remain stable enough throughout the simulation (to even 240 jet radii) and thus are plausibly representative of FR II sources.

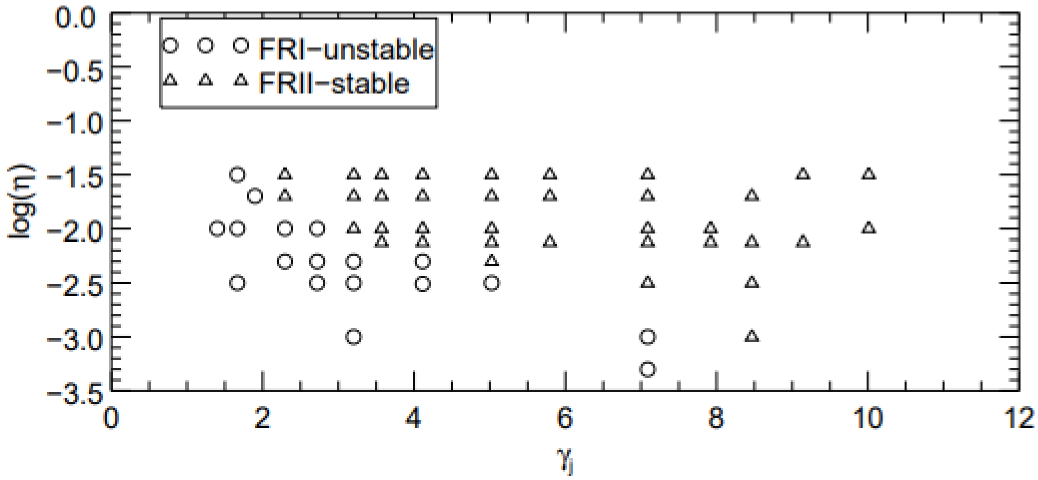

Figure 3: A still-on-going summary of the stability of our at least 54 jets. The x-axis is an alternate way of expressing v_j (the larger value corresponds to a faster jet) and the y-axis is a long scale of $\eta = \rho_j/\rho_a$. Circles represent FR I runs which have unstable jets; triangles are FR II runs with stable jets.

RESULTS AND ANALYSIS

On this project, of all the simulations produced I was chiefly tasked with generating the FR I type jet simulations and studying their characteristics. So rather than analyzing data from several runs and determining results, we will examine one FR I jet simulation from different perspectives and draw conclusions using this approach. The jet we will focus on had parameters $\eta = 0.01$ and $v_j = 0.80c$, and a resolution of 600 x 500 x 500.

The first step in analyzing any run is always identifying if the jet goes unstable and if so, finding precisely when it does. In this specific case, we suspected our jet would be of the FR I variety which it was so thus we concerned ourselves with finding the point of instability. If we look at a short time lapse of the simulation, figure 4, we see the jet begin stable at t = 0 and remain so up until approximately t = 300. Not shown, the jets goes unstable around t = 330, but at t = 600 it is clear the jet has lost its stability. As time goes on we continue to see the jet in its entirety propagate toward the edge of the grid, but the jet end has come to a stop at around 30 jet radii while both the cocoon (light green region) and bow shock (violet region) continue to propagate, now more slowly, toward the edge of the grid. Having identified the location of instability (30 jet radii), we compare the simulation to similar FR I type runs, one with the same v_j, but a greater η, and one with the same η, but a lower v_j. By doing so we can draw conclusions about the significance of the two parameters η and v_j and how they affect each jet.

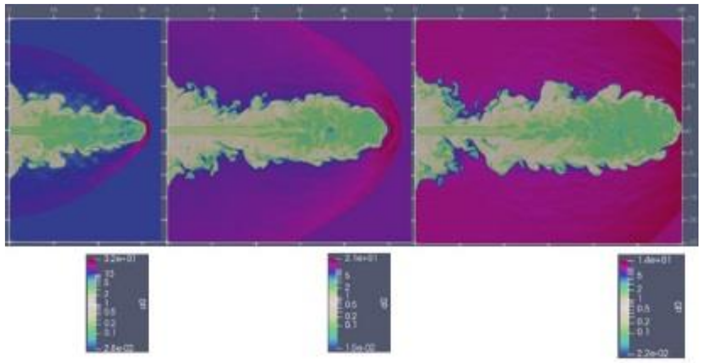

Figure 4: 3D density slices of jet simulation with parameters v_j = 0.80c and η = 0.01. Shown at different times, this FR I type goes unstable around t = 330.

First comparing the original run (η = 0.01 and v_j = 0.80c) to a run with parameters η = 0.0316 and v_j = 0.80c we see that the run with the higher η and thus higher density propagates across the grid more than twice as fast, but also goes unstable quicker (figure 5 left). Now comparing the original run to a run with parameters η = 0.01 and v_j = 0.70c we find as expected the slower jet propagating more slowly, but more interestingly we see the jet go unstable quicker as well as its cocoon never actually reaching the edge of the grid even after nearly double the time (figure 5 right).

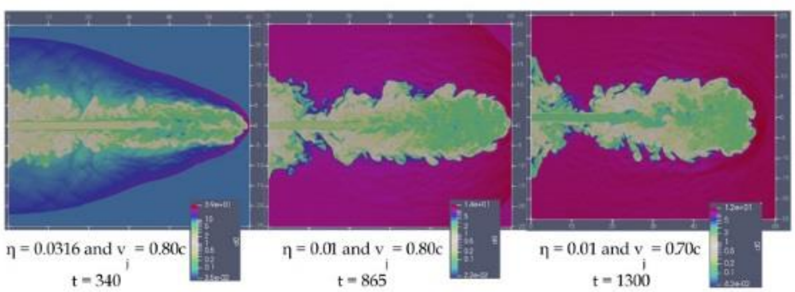

Figure 5: (center) The same run as in figure 4. We are comparing it to the runs on either side of it. (left) A jet simulation with the same v_j, but different η. (right) A jet simulation with the same η, but different v_j.

From even this brief analysis we can easily see the great significance that η and v_j have in determining the stability of a jet, but also how it propagates across the grid. Knowing this and using our chart from figure 3 we can more accurately determine what types of three-dimensional jets are FR I and what types are FR II. In summary, unstable FR I type morphologies are produced by slower and/or lower density jets while faster/higher density ones yield FR IIs.

In addition to examining the jet morphologies, as mentioned previously, our work here on 3D RHD simulations follows our previous 2D RHD relativistic jet simulations (Pollack et al. 2016). Based on what we found, it is worth discussing how the two simulation types compare and why we are justified in assuming three-dimensional modeling is superior. To start, we found that 2D simulations are actually more symmetric than 3D ones as fewer instabilities can be excited in the former. We also found that 2D simulations take longer times to cross the entire grid and their jet ends are much further behind their corresponding bow shocks than they are in the 3D simulations. The biggest difference we found is that 2D simulations inflate much wider bow shocks and cocoons and therefore we lose information off the grid along the upper and lower boundaries. As expected, we discovered in comparing 2D to 3D that the differences are small, that the 3D approach is not only valid, but indeed superior.

CONCLUSION

We have simulated an exceptionally large suite of over 50 3D RHD propagating jets using the Athena code. Our simulations of propagating jets have spanned a significant range of velocities (0.7c − 0.995c) that cover the great majority of the velocities deduced for radio galaxies (e.g. Lister et al. 2009). These flows are light, as is appropriate to radio jets, with jet density to ambient medium density ratios (η) between 5.0×10^{-4} and 3.2×10^{-2} . Both medium resolution (5 zones per jet radius) and high resolution (10 zones per radius) simulations have been completed extending out to 60, 120, or even 240 jet radii along the direction of motion; in all cases our simulations had widths of 50 jet radii in the two perpendicular directions so there was no loss of matter out of the grid along those transverse boundaries or the need to worry about waves reflecting off those boundaries and unphysically distorting the jet flow.

These simulations span a sufficient range in power so that the weaker ones go unstable before they pass through our simulation volumes. When scaled to the appropriate extragalactic dimensions and parameters these cases yield FR I type morphologies. The majority of our simulations took more advantage of the relativistic velocities computable with the Athena code and correspond to powerful sources that remain stable for very extended distances and times. On large scales these would be FR II radio galaxies and on the small scales they would be young radio galaxies. Comparison between our standard 3D RHD and 2D RHD simulations were also made and they show that 2D simulations have wider bow shocks and cocoons and take longer to propagate across the entire grid than do 3D ones.

In the future we plan to enhance the resolution capabilities of our simulations. We also plan to use a C++ version of the Athena code, Athena++, to perform simulations that incorporate magnetic fields and general relativistic effects. With these additions our models of the jets will be even more accurate.

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