Investigating the Quantities and Environments which Affect Astrophysical Jet Systems

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ABSTRACT
The large variety of environments, composition, and parameters that describe astrophysical jets form an interesting field of study and provide insight into a wide variety of astrophysical processes. We present an exploration and comparison of the different categories of jets found in different astrophysical environments. From here, we narrow our focus to an investigation of radio-loud Active Galactic Nuclei sources; particularly focusing on radio galaxy jets. We then explore the historical classification dichotomy (the Fanaroff-Riley classification scheme) in these particular sources and investigate what mechanisms may be responsible for the different appearances found between these two classes of sources. We find numerical and observational support for the jet-to-ambient density ratio playing the dominant role in the difference between these groups. To complete this investigation, we present a series of FLASH simulations which investigates underdense and overdense jet models to see the effects on the behavior and structure of the jet systems. We find some degree of support for the density dominant interpretation for the Fanaroff-Riley dichotomy, which is significantly limited by the simplicity of our model and its inability to model the full physics which take place in radio galaxy jets.

Key words: galaxies: jets, stars: jets, ISM: jets and outflows, galaxies: active

1 INTRODUCTION

Astrophysical jets are present in a wide variety of astronomical environments and provide important insight into a wide variety of physical processes. From young stellar structures, to the hearts of active galaxies, these phenomena play an important role all throughout our universe and yet many questions about the composition and parameters which govern them are not fully understood.

In this work we present an overview and background of the many different types of astrophysical jets. We discuss comparisons between the many different classifications but focus on the distinctions between jets originating from Young Stellar Objects (YSOs) and those propagating from Active Galactic Nuclei (AGN). We focus on this distinction as the YSOs provide a comparably better understood composition, and thus better understood behavior when compared to jets originating from radio-loud AGN sources.

As these radio-loud AGN sources provide so many open questions of interest, we take a deeper dive into these systems, and focus our investigation on radio galaxy jets. We explore the Fanaroff-Riley (FR) classification scheme and research the current state of understanding on the physical origin of this dichotomy.

All of this is presented in the Backgrounds section (2) of this report. To complete our investigation, we provide a sample suite of FLASH simulations to investigate the relevant jet and environment system parameters which most influence the behavior of basic jet models and describe what parallels can then be drawn to the open questions in astrophysical jets like the FR sources. We present the methodology used in creating these simulations in the Methods section (3) below. The results and discussions of these simulations and their potential impact on the broader questions found in the literature are discussed in sections 4 and 5 respectively. Finally, we conclude with an overview of our findings in the Conclusions section (6).

2 BACKGROUND

2.1 Active Galactic Nuclei

The phenomena of jet propagation occurs in a variety of astrophysical environments, all with their own peculiarities. Perhaps one of the most complex and notable progenitors of astrophysical jets lies in the form of AGN. AGNs are defined as galaxies which exhibit strong and broad emission line features (as opposed to the dominance of stellar emission and absorption features from HII regions in most galaxies) characteristic of emitting gas with large velocity dispersion (Massaglia 2009). This non-thermal emission is the dominant spectral feature and originates from the nucleus of the galaxy and extends beyond the optical band, across the entire electromagnetic spectrum.

These AGNs come in many flavors, but are most commonly classified by the strength of the emitted radio power of the AGN (Massaglia 2009). Radio quiet AGN consist of the Seyfert galaxies (Type I and II) and radio quiet quasars (QSOs). Radio loud AGN consist of radio galaxies, radio quasars, BL Lac Objects, and Optically Violent Variable (OVVs). Radio galaxies in particular are the main focus of this investigation and their properties and subdivision will be discussed in subsections 2.3 and 2.4 below.

With so many different types of AGN and classification schemes, it

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became useful to discuss some physical interpretations for the many different types of sources being observed. Much discussion revolved around whether the differences in observed spectra and appearance of these different sources originated from a physical difference in the AGN source or from observational particularities like the orientation of the source with respect to Earth.

One particularly bold approach interprets the breadth of AGN types in a single Unified Model for AGNs. While it has been posited in many different ways and expanded upon throughout the years, one of the original models of this type stems from Urry & Padovani (1995). This paper describes a model which indicates our large variety of AGN observations depend only on orientation with regard to the jet of the AGN, coverage of the nucleus by a torus of dust in the galactic plane, and luminosity of the central black hole. The specifics of this interpretation are beyond the scope of this investigation but a diagram which summarizes its content is shown below in Figure 1.

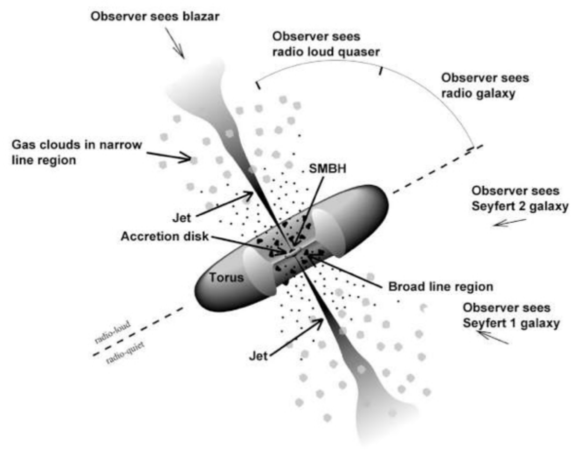


Figure 1. Diagram displaying a schematic of the unified model of AGN sourced from `https://fermi.gsfc.nasa.gov/science/eteu/agn/`.

This interpretation proposes that radio-quiet AGNs have little to no jet activity, especially when compared to radio-loud AGNs. Radio-loud AGNs are thus the clear choice for an investigation of jets originating from AGN systems. We focus particularly on radio galaxies in this group due to a particularly interesting dichotomy in their classification as well as their strong jet systems that have many parameters which are not yet fully understood or constrained.

2.2 Young Stellar Objects

Before we discuss the particular focus of this investigation and explore the particularities of radio galaxy jets, it is important we discuss astrophysical jets originating from a very different environment to gain some perspective on the lack of knowledge of properties in radio galaxy systems.

Young Stellar Objects are yet another environment in which astrophysical jet systems are found. Sometimes called protostellar jets, these objects form an important baseline to understand how we can constrain information about the properties of an astrophysical jet system. Since we observe strong emission features like Hydrogen, Helium, and metal lines in the spectra of protostellar jets, we can conclude that they are composed of normal matter consisting of a standard mix of electrons and protons. We can also conclude because of this that protostellar jets produce thermal radiation and, thus, are very useful in providing a more precise and direct analysis of the mechanisms present in the jet systems. This is because spectral features provide information on the local temperature and density as well as the bulk velocity of the jet emitting matter (Massaglia 2003).

As will be discussed in subsection 2.4, radio galaxy jets display a dichotomy in their classification scheme. This type of bifurcation is not present in the case of protostellar jets. Instead, protostellar jets have a structure most similar to one particular type of radio galaxy jets: Fanaroff-Riley II systems (Massaglia 2009). The peculiarities of this particular type of system as well as the potential causes for the dichotomy are described below, but one particular mechanism proposed by Massaglia (2003) for this are shear layer instabilities like the Kelvin-Helmholtz instability. This too is described in subsection 2.5, but it is interesting to note that these systems that do not show any dichotomy may provide us with a lower bound in the jet-to-ambient density ratio.

2.3 Radio Galaxy Jets

Radio galaxies, as the name suggests are AGN characterized by radio emission driven by jets. This emission is the product of synchrotron radiation and indicates the presence of magnetic fields and highly relativistic electrons and/or positrons (Hardcastle & Croston 2020). These objects display large-scale jets and great lobe structures driven by these central outflows.

Direct observations of these objects can provide us with radio luminosity, the size of the objects, the morphological brightness distribution, and the polarization of radio emission (Massaglia 2009). We can derive many important physical parameters from these observations, but a great deal of jet properties can't be directly constrained by this information. As mentioned in 2.2, thermal radiation allows for more direct determination of the physical properties of the matter producing the radiation and spectra. Radio galaxies though are dominated by synchrotron (non-thermal radiation) and, thus, we must make many jet parameter estimations through alternative methods.

Properties such as the magnetic field of the system thus have to be derived from the minimum-energy assumption. These can be calculated from the model for the energy density of radio emissions given by (1) below.

$$U = kJ(\nu)B^{-(p+1)/2} + \frac{B^2}{2\mu_0} \tag{1}$$

Here, k is a constant which incorporates many different physical and mathematical constants, $J(\nu)$ is the volume emissivity, B is the magnetic field strength, and p is the energy index for a power-law distribution of electron energies. Thus, noting this energy density relationship has a minimum at some minimum value of B, the characteristic magnetic field strength can be calculated by assuming the minimum energy for the system. Deviations from this assumption though would lead to a significant underestimate of the strength of the field, which makes this value not particularly well-constrained (Hardcastle & Croston 2020).

The kinetic power of the jet is derived from the work required to make space for the large lobe structures out of the ambient medium (Massaglia 2009). This approach relies on X-ray observations of the cavities and estimates of pressure derived from X-ray spectral fitting. This of course means that when these expensive X-ray observations are not available, as well as when cavities are not observed, then this method does not work. This method also does not take into account shocks driven into the external medium and also relies on poorly constrained source ages which leaves the parameter largely unconstrained itself (Hardcastle & Croston 2020).

The velocity of the jet is calculated by proper motion observations as well as by the difference in flux of the approaching and receding jets. The jet density is calculated via validation from numerical simulations and seeing which densities in simulations reproduce the structure of jet systems we see in astronomical observations (Massaglia 2009).

The environment of the jet and its associated density and pressure are also an important factor in jet evolution and, thus, an important descriptor of a radio galaxy. These environment parameters are derived from deprojecting the observed X-ray surface brightness profile. The assumption which this method relies on is that the environment's density and pressure are dominated by the X-ray emitting gas contributions. This deprojection is also typically a spherical deprojection, which means that deviations from spherical symmetry also play a role in limiting the constraints on these parameters (Hardcastle & Croston 2020).

As we can see, there are many associated uncertainties with the study of radio galaxies and their jet systems. Numerical simulations have come a long way in their ability to help probe and explain the many different peculiarities observed in these astronomical objects but they still remain a source in need of a great deal of further investigation.

2.4 Dichotomy of Fanaroff-Riley Systems

Within this population of radio galaxies exists a great variety of properties and sources among the different objects. This breadth of properties is separated into two main groups, described in this section as the Fanaroff-Riley (FR) classification scheme.

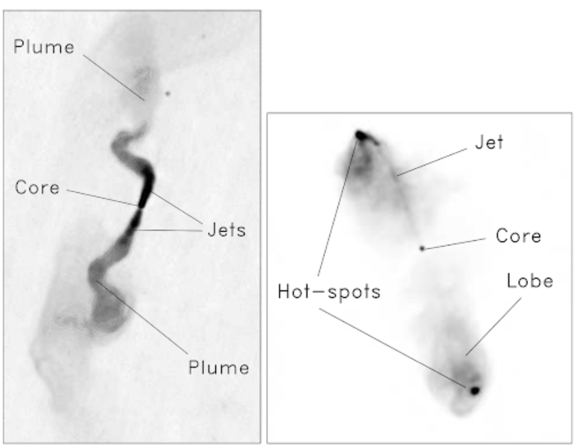


Figure 2. Figure 2 of Massaglia (2009) VLA radio images of FR I and FR II sources respectively

This scheme is based on radio morphology of the sources and is displayed in Figure 2. Sources are separated into FR I and FR II systems, based on the appearance of their radio emission structure. FR I systems are preferentially found in rich clusters and are typically associated with weak-lined galaxies. These systems show jet-dominated emission and a two-sided jet structure (Massaglia 2009). FR II systems are typically found isolated or in poor clusters and are typically associated with strong emission-line galaxies. These systems display lobe-dominated emission and a one-sided jet structure (Massaglia 2009). This difference in structure in the radio emission of these two classifications gives FR I systems the term center-brightened galaxies and FR II systems the term edge-brightened galaxies.

This morphological divide is believed to be due primarily to jet dynamics (Hardcastle & Croston 2020). FR I systems are thought to host initially relativistic jets that decelerate over the large kpc scales of their expansion. FR II systems are thought to have jets that remain relativistic throughout their entire expansion, eventually terminating in a hotspot. FR systems appear to display a great deal of similarity and relativistic flow conditions at the parsec scale (Bicknell 1995). This divide is thus thought to be a consequence of the interplay between the power of the jet and the density of the environment surrounding it. This would mean that jets of equivalent power should remain relativistic in poor environments, but in richer, or denser, environments decelerate and expand to form turbulent plumes like seen in FR I systems.

Three dimensional numerical studies of the onset of nonlinear growth of unstable modes in relativistic fluid jets propagating into a uniform medium seem conducted by Rossi et al. (2004) to support the idea that unstable perturbation can cause mixing and deceleration of the jet system. Perturbations grow as the jet expands due to the Kelvin-Helmholtz instability and induces a mixing between the jet and environment which transfers part of the jet momentum to the ambient and thus leads to an overall jet deceleration (Rossi et al. 2004). This process appears to depend strongly on the ratio between ambient and jet density, finding that underdense jets were substantially decelerated (Massaglia 2009).

These simulations seem to lend support to the interpretation that this dichotomy is governed by the jet interaction with the ambient environment. The density ratio between jet and environment being the dominant factor in jet deceleration seems to suggest a lower jet density compared to the surrounding ambient density is present in FR I sources which produces the deceleration and turbulent plumes seen in observations. This interpretation does find support in some observational samples of FR systems, including those conducted by Ledlow & Owen (1996) which finds a break in FR I/II luminosities dependent on the host-galaxy magnitude. This survey finds that FR I systems have higher radio luminosities in brighter host-galaxies which in turn is assumed to correspond with a higher density of the ambient ISM. This may seem like a clear confirmation of this interpretation of the dichotomy, however it is important to note that many of these samples were strongly flux-limited and suffered a number of selection effects so there is still a great deal of uncertainty (Hardcastle & Croston 2020).

Despite this, there is still a great deal of support for the role of shear-layer instabilities like Kelvin-Helmholtz in the deceleration of the jet as it expands into the ambient. This process appears to be strongly connected with the density ratio between ambient and jet and this will be a primary focus of our investigation.

2.5 Kelvin-Helmholtz Instabilities

One last point of consideration before beginning our own analysis on jet propagation is an understanding of the Kelvin-Helmholtz instability. The Kelvin-Helmholtz instability is a hydrodynamic instability which arises at the boundary of two fluids with some velocity shear. The velocities of the two fluids may be uniform within their own layer but form a discontinuity at the interface between them. This discontinuity in velocity induces some vorticity at the interface which causes an unstable vortex which gradually rolls up into the characteristic spirals.

This instability shows up in a great deal of astrophysical contexts in which two fluids interact, so it should come as no surprise that they play a role in the dynamics and evolution of radio galaxy jet systems. This instability has been studied at length and a number of numerical simulations have been conducted to show the great deal of importance magnetic fields play in the effectiveness of the instability on the jet systems as well as the number of dimensions used to model the behavior of the jet. A full investigation of the magnetohydrodynamic Kelvin-Helmholtz instability is outside the scope of this paper but the works of Frank et al. (1996) and Ryu et al. (2000) do an excellent job discussing the role of these more realistic and detailed environments play in the efficiency of this instability.

Hydrodynamic simulations of supersonic jet systems have given some indication of the relationship between the efficiency of the Kelvin-Helmholtz instability in the mixing and deceleration of a jet into the ambient medium. Bodo et al. (1994) has provided one such investigation, finding that heavier (overdense) jets do not suffer as much momentum loss, and thus experience a less effective deceleration due to the Kelvin-Helmholtz instability.

3 METHODS

Our primary source of investigation was through the creation of a FLASH simulation to model a primitive jet propagation into an ambient medium system. This method fails to capture the full physics required to explain the astrophysical phenomena but will suit to provide us some information on this topic for the purposes of this report.

The main point of interest that we investigate in our simulation is the effect of jet and ambient density ratio has on the propagation of the jet system. As noted in 2.4, this ratio plays an important role in the efficiency of shear-layer instabilities in decelerating the jet. It is expected from previous simulations that the Kelvin-Helmholtz instability will be more effective at decelerating the jet and creating structures more similar to the FR I systems and their turbulent non-relativistic plumes.

3.1 Simulation Model

We chose the existing FLASH jet configuration scheme designed by Ha et al. (2005). This model is designed to simulate a high Mach number astrophysical jet with a radiative cooling scheme. This model is characterized by the equations of gas dynamics in equations (2)–(4) below.

$$\frac{\delta\rho}{\delta t} + \frac{\delta}{\delta x_i}(\rho u_i) = 0 \tag{2}$$

$$\frac{\delta}{\delta t}(\rho u_j) + \frac{\delta}{\delta x_i}(\rho u_i u_j) + \frac{\delta P}{\delta x_j} = 0 \tag{3}$$

$$\frac{\delta E}{\delta t} + \frac{\delta}{\delta x_i}(u_i(E+P)) = -n^2\Lambda(T) \tag{4}$$

Here, we have $\rho = m_H n$ as the density of the gas which is assumed to be Hydrogen dominated, n as the number density, u_i as the velocity, ρu_i as the momentum density $P = nk_BT$ as the ideal gas pressure, and $E = \frac{3}{2}nk_BT + \frac{1}{2}\rho u^2$ as the energy density (Ha et al. 2005).

This model also assumes a polytropic equation of state given by equation (5).

$$P = (\gamma - 1)(E - \frac{1}{2}\rho u^2) \tag{5}$$

where $\gamma = 5/3$ for a monatomic gas, which is the case in this model which assumes a Hydrogen composition. Additionally, this model incorporates radiative cooling via the $\Lambda(T)$ term which is defined in (6).

$$\left(\frac{dE}{dt}\right)_{cooling} = -n^2\Lambda(T) \approx \begin{cases} -\tilde{\Lambda}(P^2 - P_a^2), & T > T_a \\ 0, & otherwise \end{cases} \tag{6}$$

where $\tilde{\Lambda} = 8.776$ in the computational units of this scheme and P_a and T_a are the ambient pressure and temperature respectively. This approximation is observed to be invalid at high temperatures greater than roughly $10^6 K$.

It is also worth noting that this simulation scheme uses its own computational units. These are defined in Table 1 below.

Physical Quantity	Basic Scale
Length	$\bar{l} = 10^{11}$ km
Time	$\bar{t} = 10^{10}$ s
Velocity	$\bar{u} = 10$ km/s
Density	$\bar{\rho} = 100\ H/cm^3$
Energy Density & Pressure	$\bar{E} = \bar{P} = 104.4\ eV/cm^3$
Temperature	$\bar{T} = 12115$ K

Table 1. Table 1 from Ha et al. (2005) displaying the computational units for their jet simulation scheme. We adopt this same configuration for our model.

We use this scheme and configuration to run our own investigation in FLASH. The specific parameter values and resulting jet behavior is displayed in Section 4 below.

4 RESULTS

Our simulation models are split into two main cases: those with underdense jet schemes, meaning a jet-to-ambient density ratio less than unity, and those with overdense jet models, meaning a density ratio greater than unity. We display the results and model parameters in subsections 4.1 and 4.2 below.

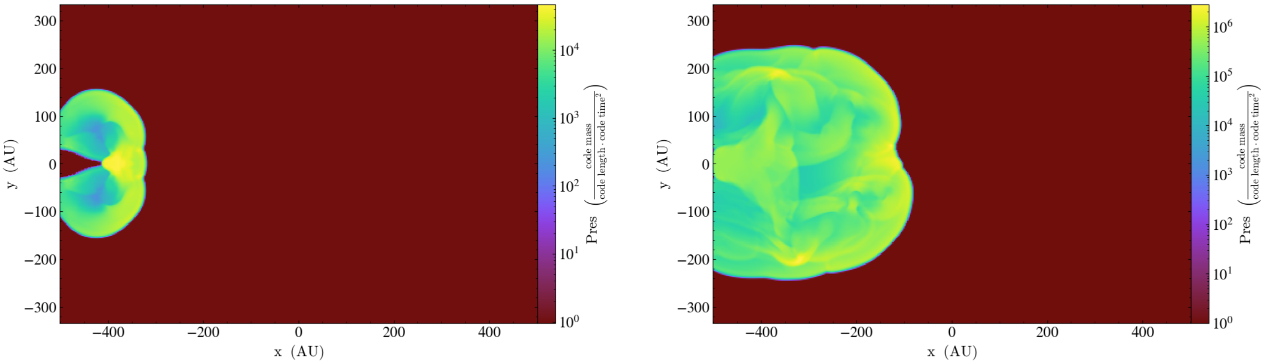
Since our main parameter of interest is the density ratio and exploring what effect this has on the behavior of the jet system and its interaction with the ambient, we keep a number of parameters constant throughout our runs. These constant parameters are shown in Table 2 below.

Jet	Ambient
$\gamma = 5/3$	$\gamma = 5/3$
$u_j = 80$	$u_a = 0$
$P_j = 1$	$P_a = 1$
$r_j = 0.1$	–

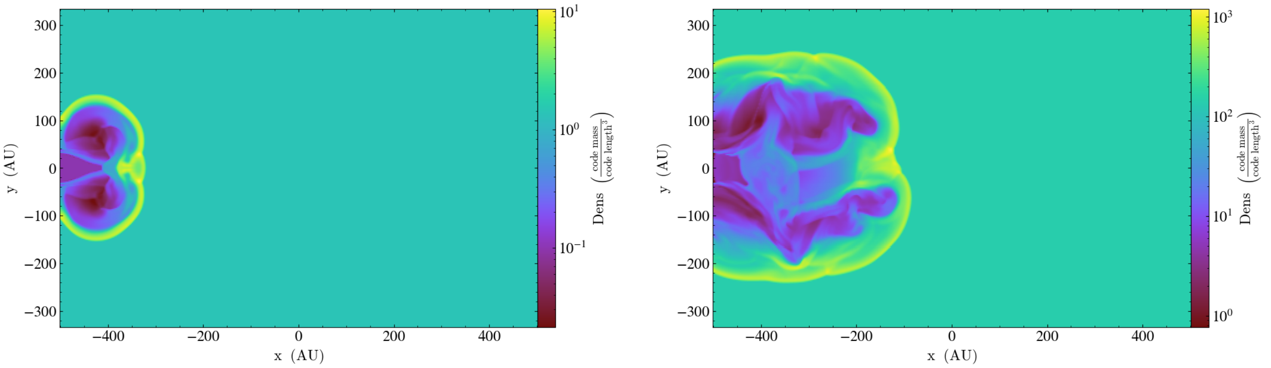
Table 2. Table displaying the common parameters used to define our jet simulations. The units for these values are the same code units from Ha et al. (2005) discussed in Table 1. Almost all of these parameters above are the same quantities described in the governing equations for the model, the only new addition is r_j which is the radius of the jet.

4.1 Underdense Models

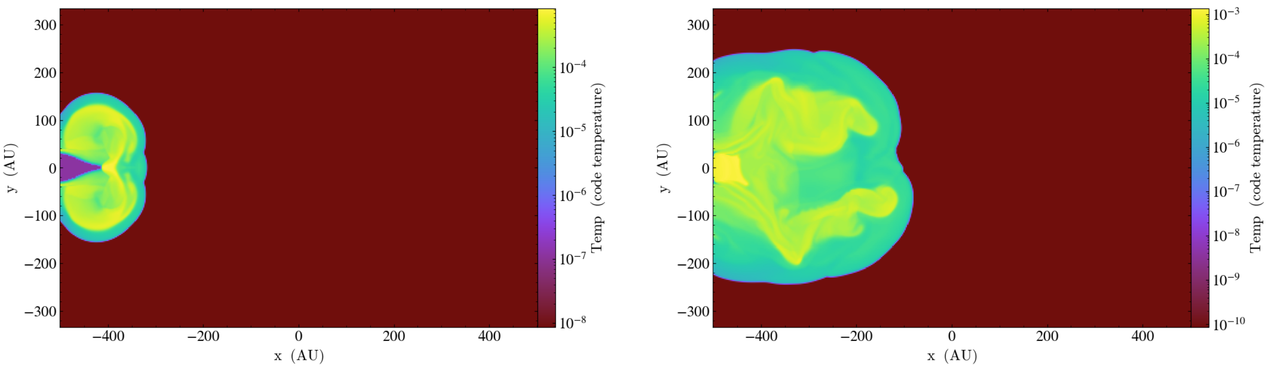
An underdense simulation model I investigated was one in which a jet is moving into a stationary ambient medium. This simulation model had a jet-to-ambient density ratio of 1:10. The exact parameter details are given in Table 3 and the results of this simulation are displayed in Figure 3 below in the form of temperature, pressure, and density plots of two time slices of our simulation run.



(a) Pressure plots of the underdense jet simulation.



(b) Density plots of the underdense jet simulation.



(c) Temperature plots of the underdense jet simulation.

Figure 3. Simulation with a jet-to-ambient density ratio of 1:10. Two different time slices are shown, one early in the evolution of the jet where the roll-up phenomena begins to take shape and the evolution corresponds to the same time step as the overdense jet slices below. The other is later in the jet evolution where a great deal of mixing and expansion has occurred.

Jet	Ambient
$T_j = 1$	$T_a = 0.1$
$\rho_j = 0.1$	$\rho_a = 1$
$c_{s,j} = 4.1$	$c_{s,a} = 1.3$

Table 3. Table displaying the underdense jet model parameters used in our simulation. The units for these values are the same code units from Ha et al. (2005) discussed in Table 1.

To calculate the Mach number of these jets we utilize the common jet velocity given in Table 2 and the sound speed of the medium, where we take the Mach number as being relative to the sound speed of the jet material by convention showing us that this is a Mach 19.6 jet.

4.2 Overdense Models

An overdense simulation model I investigated was one in which a jet is moving into a stationary ambient medium. This simulation model had a jet-to-ambient density ratio of 10:1. The exact parameter details are given in Table 4 and the results of this simulation are displayed in the pressure, density, and temperature slices for the simulation shown below in Figure 4.

Jet	Ambient
$T_j = 0.1$	$T_a = 1$
$\rho_j = 1$	$\rho_a = 0.1$
$c_{s,j} = 1.3$	$c_{s,a} = 4.1$

Table 4. Table displaying the overdense jet model parameters used in our simulation. The units for these values are the same code units from Ha et al. (2005) discussed in Table 1.

To calculate the Mach number of these jets we again utilize the common jet velocity given in Table 2 and the speed of sound in the jet medium. Using these values, we see that our overdense jet scheme is a Mach 62.0 jet.

5 DISCUSSIONS

5.1 Simulation Findings and Relevance

It is the interaction with the ambient medium as the jet expands on larger scales which then causes a deceleration to eventually non-relativistic speeds and the formation of turbulent plumes that we see in FR I systems. As we found in Section 2.4, this process appears to be governed by the jet-ambient density ratio which plays the dominant role in the efficiency of deceleration.

We do note a visible difference in jet structure between the underdense and overdense cases when evolved to the same time step, which does favor a more significant roll-up in underdense schemes and supports the expectations of this interpretation of the dichotomy of FR systems. This can be seen from the very early onset of roll-up effects in the underdense jet case.

We also see that the underdense jet case undergoes significant structural change as well when comparing the structures of the two jet cases across their evolution. The overdense jet is also able to propagate much further into the ambient medium than the underdense jet. This is indicative of a great loss of energy and deceleration undergone by the underdense jet which is exactly what is expected by the jet-ambient density deterministic interpretation of FR systems. We thus find some, weak support for this theory of the FR dichotomy as we do see underdense jet schemes giving rise to a greater deceleration of the jet overall which is expected to be the environments which produce FR I systems.

However, unlike what this theory predicts, we do not see strong evidence of the Kelvin-Helmholtz instability and its trademark spiral structures taking place at the jet interface and governing deceleration throughout the evolution of the jet. While we do see the expected mixing of the material and the deceleration associated with FR I systems in the underdense simulations, the lack of evidence of the shear layer instabilities which are expected to mediate the evolution into this structure do not allow us to clearly show support for this intepreation from our toy model simulation.

It is important to note too that our model does not reproduce the full structure of these FR systems, which is likely a symptom of the simplicity and limitations inherent in this scheme not capturing the full physics which describe radio galaxy jet systems. These limitations are discussed in depth in subsection 5.2.

5.2 Limitations of Our Model

Despite the bits of insight we've gained from our simulations, we must note there are significant limitations in applying them to the broader context of radio galaxy jet systems.

First of all, we note that even though these are high Mach number jet simulations, they are still well-below the relativistic speeds at which both classifications of FR systems begin at. As stated in 2.4, one popular interpretation for the dichotomy in FR systems is that, at equivalent powers, both systems begin relativistic and maintain similar structure on parsec scales. This is certainly not the case in our simulations. The speed of our jets are in the hundreds of km/s and, thus, never reach any significant fraction of the speed of light.

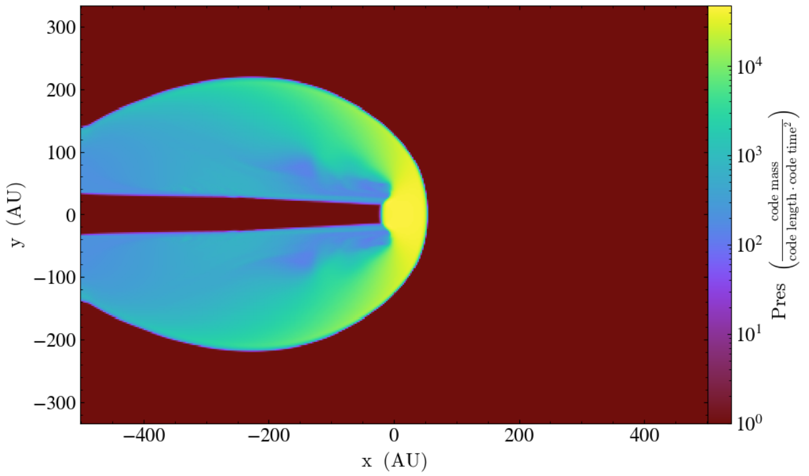
We also note that magnetic fields play an important role in the emission, composition, and acceleration of radio galaxy jet systems as we discussed in subsection 2.3. Our simulation model, however, does not include any magnetic fields and is thus purely hydrodynamical, which means we are missing a significant component of jet evolution required to accurately model these astrophysical systems.

These discrepancies between simulation model parameters and the actual parameters expected for radio galaxy jets are partially an artifact of the original intentions of the model. As mentioned, the original model is modified from Ha et al. (2005). The intent of their investigation was not to accurately model or investigate radio galaxy jets, but instead another type of astrophysical system. Their model was intended to reproduce the conditions of HH 1-2 jet systems, and these are a type of luminous protostellar jet. As mentioned in subsection 2.2, protostellar jets have many different characteristics than radio galaxy jets. These discrepancies do raise some concerns about the applicability of our simulation model to the larger investigation of radio galaxy jet systems but still provide some degree of confirmation for the already well-supported interpretation of the evolution and dichotomy found in these systems.

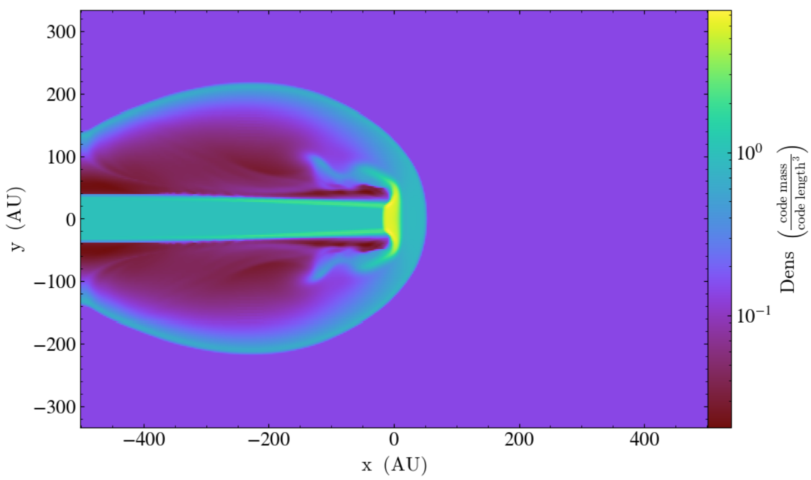
6 CONCLUSIONS

Astrophysical jet systems provide a wide array of environments to test and explore our understanding of many different physical processes. One particularly interesting class of astrophysical jets which served as the basis of this investigation were those originating from AGN systems. We particularly focus on the radio galaxy component of this class due to the many unanswered questions regarding the structure and properties of the jets. Many properties of these jets require a great number of assumptions, which leaves many key parameters unconstrained and leaves a great deal of uncertainty on the processes which govern them.

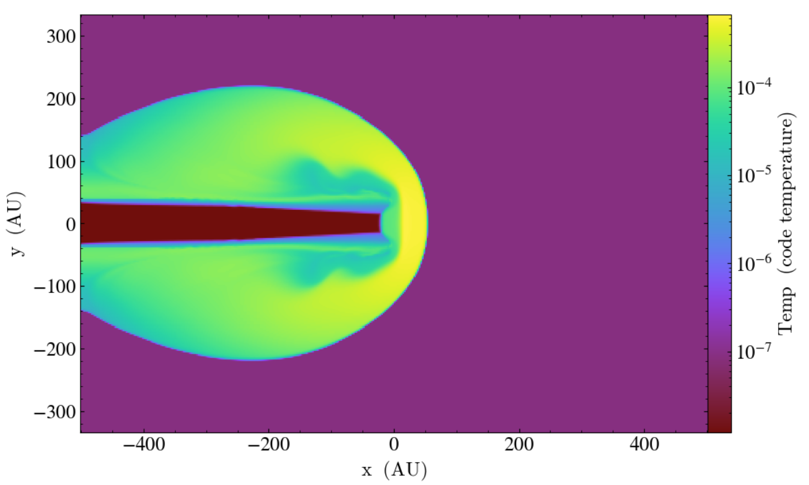
One particularly important feature of this group of jets is the FR classification scheme. This scheme divides radio galaxy jets based on the radio morphology of each jet system. FR I systems show jet dominated emission and a two-sided jet system which terminate in turbulent plumes. FR II systems display lobe dominated emission and a one-sided jet structure. The processes responsible for this dichotomy isn't entirely understood, though many different interpretations attempt to explain this. One such interpretation which has garnered a great deal of observational and numerical support is the interpretation that at short, parsec scales, with equivalent power jets, FR I and II systems behave the same. The process which causes the divergence in structure at larger, kiloparsec scales is thus the environment and jet interaction, particularly the ratio of their densities. This interpretation states that as a jet evolves into the ambient medium, denser environments can create a more efficient decelera-



(a) Pressure plots of the overdense jet simulation.



(b) Density plots of the overdense jet simulation.



(c) Temperature plots of the overdense jet simulation.

Figure 4. Simulation with a jet-to-ambient density ratio of 10:1. Time slice shown corresponds to the same time step displayed in the left panel of figures for the underdense jet simulation.

tion of the jet through the transfer of momentum mediated by shear layer instabilities such as the Kelvin-Helmholz instability.

We adopt the jet propagation model scheme of Ha et al. (2005) to further validate this interpretation of the dichotomy in radio galaxy systems. Our models do show some degree of confirmation for this interpretation. We see greater evidence of mixing and deceleration of the underdense jet when compared to the overdense jet scheme. Stronger evidence for jet deceleration and structural deformation for underdense jets is exactly what is expected to reproduce the FR I systems in the dichotomy theory. However, we also note a lack of clear evidence of the Kelvin-Helmholtz instability and associated shear-layer structure which is expected to mediate the transfer of momentum and mixing with the ambient environment of the underdense jets in these astrophysical systems.

We also note though that any evidence from our model must be taken in hand with the strong limitations of our simulation scheme. These limitations mainly correspond to a lack of appropriate velocity and magnetic field properties to accurately explain the physics within a true radio galaxy system.

ACKNOWLEDGEMENTS

I would like to thank Dr. Petros Tzeferacos for his guidance in selection and exploration of the topic of astrophysical jets. This has been an incredibly interesting investigation and I really appreciate the help along the way. Thank you as well for a great course!

DATA AVAILABILITY

The simulation scheme and suite of different parameter files are available in my GitHub repository: `https://github.com/mattwanink12/ASTR462Sim`.

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