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A Study of Plasma Jets Formed by Astrophysical Shocks and an Investigation of the Relationship between Instabilities and Jet Propagation

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Abstract

Scientists are investigating the astrophysical shock phenomena responsible for the origins of plasma jets while also working to determine the relationships between these jets and the instabilities they produce. Galactic energy jets emitted from active galactic nuclei provide energy that reshapes our understanding of galaxy evolution, influencing how gas clusters cool and how supermassive black holes transform. Through extensive research and online resources, scientists have demonstrated the fundamental processes involved in jet-surrounding medium interactions and have clarified the structural dynamics of plasma jets. However, the initial cause of the Fanaroff–Riley (FR) morphological division, distinguishing between (FRII and FRI) jet types based on size and structure, remains unknown. Gaining this understanding requires conducting global three-dimensional magnetohydrodynamic simulations of jet acceleration in matter. Jets experience delayed propagation and compression as they travel through galactic nuclei with flat density profiles, which increases the likelihood of three-dimensional magnetic curvature instabilities. This study identifies a key factor influencing jet behavior: the core's mass and radius. Under certain conditions, "leaky" behavior appears in the core, where jets stall before expanding as cavity-forming plasma regions. Once the critical force threshold is exceeded, the jets escape the core, producing strong reverse flows. The morphological features of jets and the observed (FR) dichotomy can be explained by curvature instability mechanisms. Moreover, the values of the critical forces correspond well with previous measurements of galaxy optical brightness.

Keywords: Plasma-jets, astrophysical, MHD, FR, instability jets.

دراسة النفاثات البلازمية المتكونة من الصدمات الفيزيائية الفلكية والتحقيق في العلاقة بين عدم الاستقرار وانتشار النفاثات

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الخلاصة

يدرس العلماء ظاهرة الصدمة الفيزيائية الفلكية والمسؤولة عن اصل نفاثات البلازما ويعملون على تحديد العلاقات بين هذه النفاثات واللاستقرارية الناتجة عنها حيث تنبعث هذه النفاثات من النوى المجرية النشطة طاقيا والتي تعيد تشكيل فهمنا في كيفية تحول وتطور المجرات من خلال تأثيرها على تبريد مجموعات الغاز في عناقيد المجرات وكذلك دورها في التحولات للثقوب الأسود الهائلة. تمكن العلماء من توضيح جميع العمليات الأساسية لتفاعلات الطاقة النفاثة المحيطة بالوسط وشرح الديناميكيات الهيكلية لنفاثات البلازما من خلال البحوث والمحاكاة الحاسوبيةلكنهم فشلوا في العثور على السبب الرئيسي لانقسامات فاناروف– رايلي (FR) المورفولوجية والتي تميز بين نوعي (FRI و FRII) اعتماداعلى الحجم والبنية. يتطلب فهم هذا الامر إجراء محاكاة مغناطيسية هيدروديناميكية ثلاثية الأبعاد شاملة لتسارع النفاثة وانتقالها عبر المادة المجرية كما تكشف هذه المحاكاة ان النفاثات تبطى وتتعرض للانضغاط اثناء مرورها عبر نوى مجرية ذات كثافة مسطحة مما يزيد من احتمالية نشوء لااستقراريات انحناء مغناطيسي ثلاثية الأبعاد. حددت هذه الدراسة عاملا رئيسيا يؤثر على سلوك النفاثات، كتلة قلب المجرة ونصف قطرها وفي ظل ظروف معينة تظهر ديناميكيات تعرف بـ "التسرب" لقلب المجرة، حيث تتوقف النفاثات قبل أن تتمدد لتشكل مناطق بلازمية اشبه بالتجويفات وعند عبور حد العتبة الحرج للقوة، تندفع النفاثات الى خارج قلب المجرة منتجة تدفقات عكسية قوية وبالتالي يمكن تفسير السمات المورفولوجية للنفاثات والانقسام (FR) والملاحظ من خلال اليات اللاستقرارية للانحناء، فضلا عن التوافق الجيد ما بين القيم الحرجة للقوة والقياسات السابقة للسطوع البصري للمجرات بما يعزز العلاقة بين النماذج النظرية والبيانات التطبيقية.

1. Introduction

A range of interesting cosmic events in the universe happen because of plasma jets that are expelled from young stars, neutron stars, and supermassive black holes in active galaxies [1]. Jet streams move through outer space across hundreds to thousands of light-years and play a key role in shaping galaxies [2]. The uneven conditions encountered by jets do not stop them from traveling far, so some mechanism within the jets must maintain their balance [3].

When plasma jets travel at high speeds and collide with obstacles in their path, they generate astrophysical shocks, as shown in Figure (1), which help accelerate particles and amplify the magnetic field [4].



Figure 1: Plasma jet formed by astrophysical shocks [4]

This process leads to the formation of astronomical jets, exhibiting a variety of structures observable across the electromagnetic spectrum from radio waves to gamma rays. The presence of magnetic fields influences both the shape and energy distribution of the jet material [5,6]. Although telescopes, like the Event Horizon Telescope and James Webb Space Telescope, have advanced our understanding of jet launching, many aspects of jet stability remain under active debate [7]. The evolution of jets is strongly influenced by Rayleigh-Taylor and Kelvin-Helmholtz instabilities, which can alter their morphology and potentially prevent them from traveling long distances [8]. As jets interact with surrounding material, these instabilities develop, producing recognizable patterns observed both in space and in laboratory plasma experiments. Interestingly, current studies suggest that turbulence may play a role in stabilizing jets over extended periods by redistributing energy and modifying the magnetic field [9]. The evolution of jets relies heavily on Rayleigh–Taylor and Kelvin–Helmholtz instabilities, which can alter their morphology and potentially prevent them from traveling long distances [10]. When jets interact with nearby material, instabilities develop, producing well-known patterns that can be observed both in space and in plasma experiments. Interestingly, researchers have found that recent studies suggest turbulence plays a role in stabilizing jets over extended periods by redistributing energy and modifying the magnetic field [11].

2. Astrophysical Shock Dynamics

When supersonic matter enters a region of lower velocity, it causes a sudden change in the properties of the surrounding medium in astronomical environments. The interaction between particles moving faster than the speed of sound and other particles produces shock fronts also known as compression waves—that propagate through interstellar and intergalactic media [12]. The subsequent conversion of kinetic energy into heat and magnetic waves is one of the most powerful processes in the universe [13]. Shocks are ubiquitous in space and occur on a wide range of scales. Researchers have observed bow shocks surrounding Earth and Jupiter, as well as those formed by stars moving rapidly through the interstellar medium and during collisions between massive galaxy clusters [14]. Driven by the solar wind, these fundamental processes can significantly impact satellites and space missions by directing high-energy particles and altering magnetic fields [15].

Gas in giant molecular clouds is compressed when struck by shock waves, leading to the formation of stars through explosive events known as supernovae [16]. This mechanism enables fluid motions within molecular clouds to promote the clustered formation of stars, distributing them relatively evenly throughout galaxies [17]. Multiple star formation triggers can operate simultaneously, including those involving powerful jets from supermassive black holes [18]. In the physics of relativistic jet production from Kerr black holes, two primary mechanisms are used: the Blandford–Znajek process, which extracts energy from the ergosphere, and the Blandford–Payne mechanism, which draws power from the accretion disk [19]. These processes harness the immense energy stored in black holes and convert it into powerful plasma jets [20]. The jets then accelerate and become collimated, allowing them to travel vast distances far beyond their compact origins [21]. Due to the presence of high-energy radiation at kiloparsec scales, these outflows must be re-accelerated to compensate for the energy loss caused by radiative cooling [22].

Through electromagnetic studies, radio galaxies that launch jets are classified into (FRII and FRI) types [23]. These jets are characterized by tightly packed material, higher brightness, noticeable physical discontinuities, and distinct motion patterns [24]. In our research, we focus on the loss of kinetic and magnetic energy and how instabilities lead to the

formation of shocks at the edges of various structures. Shearing and mixing within these processes facilitate the acceleration of particles over different distances [25,26]. Using observational data, we have precisely identified the key factors involved in stellar wind collisions with (FRI) jets, making our approach effective for estimating the shapes of shock fronts in diverse regions of the universe. This understanding of shock waves across cosmic scales reinforces established plasma theory and provides important insights into galaxy formation, high-energy particle production, and the interconnected feedback mechanisms that shape the universe [27,28].

3. Methodology:

3.1 Instabilities in Plasma Jets:

Astrophysical jets are held together by strong magnetic forces and remain sub-Alfvénic, despite the fact that their magnetism changes to become toroidal because of the flow. During the acceleration of jets, when their space and form expand rapidly and many additional streamlines appear, the toroidal field is strongly supported by magnetic flux conservation. Once both internal and magnetic energy in a jet plasma have been used up during entrainment and bulk acceleration, the plasma moves from magnetically-dominated to particle-dominated behavior. By means of this process, the jet system acquires the foundation for certain unstable behaviors. To study instability development during its linear phase, one must first precisely linearize all the Relativistic Magneto-Hydro Dynamics (RMHD) equations and, second, account for perturbations of the wave functions at various space and time scales [29,30].

3.2 The magnetohydrodynamic (MHD) equations

3.2.1. Continuity equation

The continuity equation deals with how mass is conserved in plasma as below:

$$\partial\rho \,/\, \partial t + \nabla \cdot (\rho v) = 0 \tag{1}$$

Where ρ is mass density, v is the velocity vector, $\nabla \cdot (\rho v)$ is the mass flux divergence. In other words, the mass within a given region is only changed by the total mass that flows through its boundaries during its evolution. As a result, any change in mass within a section of plasma is always corrected by changes in mass entering or leaving the section along magnetic field lines:

3.2.2. Momentum Equation

This statement shows how to integrate pressure changes, magnetic forces acting on plasma, and other effects. In magnetohydrodynamics (MHD), the Lorentz force ensures the plasma moves along the lines of the magnetic field. This shows that groups of charges adjust to electromagnetic forces in a way that helps regulate and stabilize the strengths of the same forces they experience. In many astrophysical environments, what determines plasma's behavior is how its kinetic pressure, magnetic pressure, and tension balance work together.

$$\partial\,(\rho)\,/\,\partial\, t \;+\; \nabla \;\cdot\; (\rho\, v\, v) = -\nabla\, p \;+\; J \;\times\; B \;+\; \rho\, g \tag{2}$$

Where: p is the pressure, J×B is the magnetic force, and g is gravitational acceleration.

3.3.3. The Induction Equation

The main equation controlling magnetism in a plasma indicates how the field is frozen into the streaming plasma whenever the resistivity is close to zero. As a result of this equation, magnetic flux and plasma motions work together, allowing the whole field structure to move in tandem with the plasma. In plasma with a high conductance, advection is the main term in the equation, which helps preserve the shape of the field as plasma moves. By observing flux

conservation in space science, many explain the behavior of things like the sun's corona and the behavior of accretion disks.

$$\partial B / \partial t = \nabla \times (v \times B) - \nabla \times (\eta \nabla \times B) \quad (3)$$

Where B= the magnetic field vector, the resistivity = η, the velocity field=v.

3.3.4. Energy Equation

The following equation clearly proves that energy is conserved, outlining how changes in temperature take place over time due to various internal processes within plasma that is magnetized. It considers transport of heat via heat conduction, Joule heating in areas with currents and resistivity, and ways that kinetic, internal and magnetic field energy can change within the plasma. Using this mathematical approach, it is shown that the energy from pressure forces, electromagnetic energy, and viscous FRIction help big-scale energy balance as they allow energy to transform at certain points. The equation makes the study of plasma energization easier by showing how plasma changes and its radiative processes occur as a result of electromagnetic influences.

$$\frac{\partial}{\partial t}\left(\frac{p}{\gamma-1}+\frac{1}{2}\rho v^2+\frac{B^2}{2\mu_o}\right)+\nabla.\left[\left(\frac{p}{\gamma-1}+\frac{1}{2}\rho v^2+p\right)\vec{v}+\frac{1}{\mu_o}\vec{B}\times\left(\vec{v}\times\vec{B}\right)\right]=0 \quad (4)$$

When referring to the adiabatic index, we use a Greek letter called (γ), while (μ_o) is the symbol for the magnetic permeability. The set of (MHD) equations helps to better describe plasma motion, the changes in magnetic fields, stability, and other critical aspects vital for understanding jets and plasma in the universe. A common issue in (CDI) is that they may develop in magnetically regulated jet systems, and studies find that their spectra include various wavenumbers and frequencies, with the imaginary part indicating how fast they grow [31,32]. Although numerical approaches are strong tools for exploring both non-linear changes and post-linear growth, it is vital to have precise statistics to identify and track minor initial activities that later develop into instabilities [33]. The analysis of these equations using mathematics helps us understand the basics behind how jets form, are sped up, and gradually disperse over wide areas in the universe.

3.3.5 Numerical simulation

Zhai, Bellan, and Li developed and implemented an advanced three-dimensional code to replicate the Caltech jet experiments. Originally designed as a tool for astrophysical research, the code was adapted for the Caltech experiments by incorporating all necessary boundary conditions and physical parameters. The computer simulations demonstrated a strong correlation with real-world observations, validating the theoretical framework discussed in this study. The sequences generated by the code closely matched the data collected during the experimental phase. The simulations also accurately reproduced plasma density measurements within the jet. These results support the robustness of magnetohydrodynamic jet dynamics, aligning well with both laboratory and astrophysical observations.

Based on the mathematical model algorithm, it was found that perfect (MHD) models cannot accurately replicate the real-world conditions observed near boundaries. This limitation arises from the need to introduce electromagnetic energy at the boundaries, something not permitted under ideal (MHD) assumptions. To accurately model the magneto-plasma injection process at the electrode interfaces, the researchers introduced a localized region of non-uniform resistivity into the simulation domain. This adjustment allowed the magnetic fields and plasma within the domain to decouple, as illustrated in figure (2). The use of a modified induction equation in the (MHD) framework enabled magnetic field lines to break and reconnect within the model. By adopting this refined approach, which incorporated non-ideal aspects of (MHD), the scientists successfully captured critical physical processes occurring at interfaces where real systems deviated from classical (MHD) assumptions.

$$B_{tor} = \frac{\mu_o I}{2\pi} \nabla\psi \quad (5)$$

Where ψ = poloidal flux, I = poloidal current, B_{tor} =toroidal magnetic field.

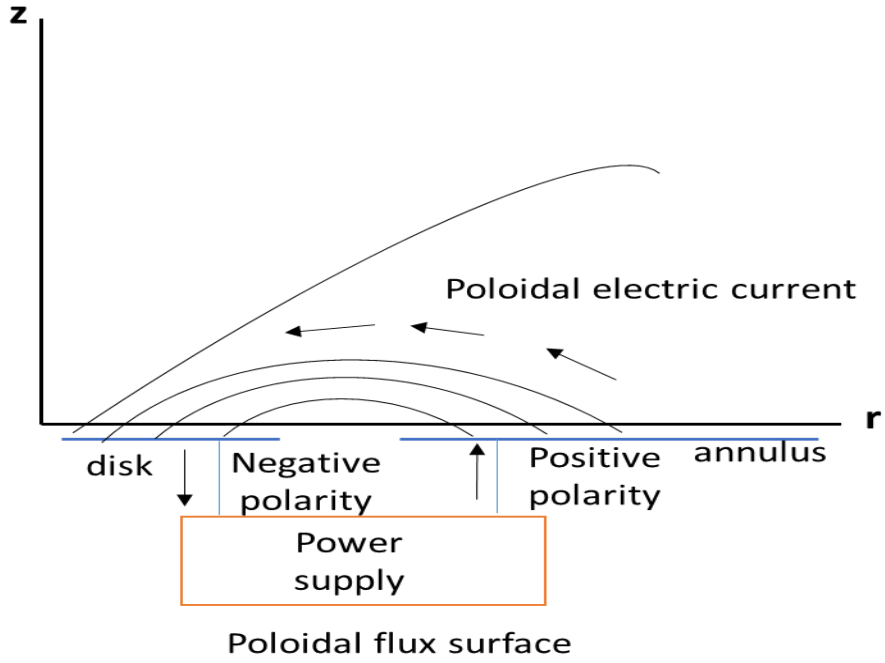


Figure 2: Gas flows from both the disk and annulus

To generate the magnetic field, a new non-physical term, referred to as a constrained generator, was added to the right-hand side of the standard (MHD) induction equation. This modification was necessary because the original theory did not align with experimental observations. Regions beyond the ($z = 0$) plane boundary were excluded, and the non-physical term was removed from the positive-z domain. Using this approach, currents were induced to flow between the interior and exterior regions of the torus due to the presence of a magnetic field throughout the entire structure. Based on these findings, it is believed that the origin of astrophysical jets may involve mechanisms that go beyond the traditional principles of (MHD). The torus-like shape of the energy configuration also makes it susceptible to disturbances and instabilities. No observational evidence has been found to suggest that parsec-scale disturbances occur, leading to several possible explanations. First, instabilities may develop more slowly than the evolving flow conditions. Additionally, instabilities might arise on extremely small scales within the jet, preventing the formation of large-scale magnetic structures. Moreover, several factors can delay the onset of destructive current-driven instabilities (CDI), such as a strong poloidal magnetic flux, significant jet expansion, the presence of intense turbulence, external winds, and minimal azimuthal velocity [34].

A reduction in magnetic energy flux and a decrease in flow acceleration can drive the jet into a super-Alfvénic state. During this phase, Kelvin–Helmholtz instabilities (KHI) become more significant than current-driven instabilities (CDI). Most previous research on parsec-scale jet structures has focused on (KHI), while more recent studies have begun to examine sub-parsec jets in greater detail [35]. Observational data have not indicated that the use of such jets has caused any significant, large-scale disruptions. Zhang et al. found that jet decollimation and deceleration could be explained by the growth of helical phase perturbations extending several kilometers within the jet [36]. Shortening the time it takes for

waves to enter and exit the jet helps suppress global instabilities [37]. The Lorentz effect explains how wave oscillations can propagate over large distances; even when jets maintain a small inclination, their perturbations can grow significantly in length. Some researchers suggest that the slower motion of (FRI) jets is linked to the disproportionate development of (CDI and KHI) characteristics [38,39]. Despite certain similarities, the two types of radio galaxies are distinguished by local instabilities in the jet, which can cause portions of the flow to recollapse inward and reach the galactic core [40].

High-frequency Kelvin–Helmholtz (KHI), Rayleigh–Taylor (RTI), and centrifugal (CFI) instabilities have been proposed as mechanisms by which a jet can expand and subsequently regain its collimation. However, even though (FRI) jets can open significantly in the deceleration (or "braking") region, there is no definitive evidence that large-scale recollimation shocks consistently occur, indicating that such events are not universal. While these instabilities do not necessarily cause a change in Fanaroff–Riley (FR) classification, they may reduce the jet's magnetic and kinetic energies, potentially leading to a gradual slowdown over time. During the linear phase of amplitude growth, energy loss due to instability is minimal and mostly associated with wave-like oscillations. However, as amplitudes enter the nonlinear stage, energy dissipation increases significantly. At this point, shocks form and turbulent mixing occurs, which can severely disrupt both the propagation and structural integrity of the jet.

$$\Lambda = \frac{2\gamma_j\theta_j}{0.03} = k * \left(\frac{l_j}{nm_p r^2 \gamma_j^2 c^3}\right)^{1/6} \quad (6)$$

While (n) is the surrounding medium's number density, (m_p) is the proton's mass, (r) is the measurement of the distance across the jet, and ($k = 20(2\pi/9)^{1/2}[\pi(5-\alpha)(3-\alpha)/6]^{1/3}$) fixed prefactor, and the slope of the diffuse density profile is denoted by ($\alpha = -d \log n/d \log r$). Unless specified otherwise, we will assume the jet plasma flows at a somewhat hyperbolic velocity ($\beta_j \equiv v_j/c \approx 1$) and ($\gamma_j = (1-\beta_j^2)^{-1/2}$) is strongly magnetic ($\sigma \gg 1$). According to equation (1), densely combined jets are the most vulnerable to kink instability [41-43]. If ($\Lambda < \Lambda_{crit.} \equiv 2$ or $\theta_j < \theta_{crit.} \equiv 0.03/\gamma_j$), these kink instabilities have enough time to grow before disrupting and stalling the jets. This study analyzes two representative models known as (P44) (model P44HR is a high-resolution version of the (P44) model) that demonstrates a jet power of ($L_j = 1.5 \times 10^{44}$ erg s^{-1}) along with (P46) that illustrates a jet power of ($L_j \approx 1.5 \times 10^{46}$ erg s^{-1}). The starting diffuse density profile appears in Figure 3(a). A power law distribution that follows ($n = nkpc(r/kpc)-\alpha$) describes the core region of spiral galaxy types like (M87) with a typical normalizing factor ($nkpc = 0.2\ cm^{-3}$)and slope value ($\alpha = 1$). We selected model (P46B2) because its density profile develops a steeper slope outside the central area ($r > r_{break}$). The density is divided by the factor ($^{(r/r_{break})-1.5}$). We use ($r_{break} = 10^2\ r_{in}$), which provides a reasonable scale difference between ($^{r}_{in}$ and $^{r}_{break}$) (Table 1). Our models may be adjusted for various jet powers and surrounding densities by adjusting the length unit and keeping($\Lambda_{in} = \Lambda(r_{in})$) constant (Table 2).

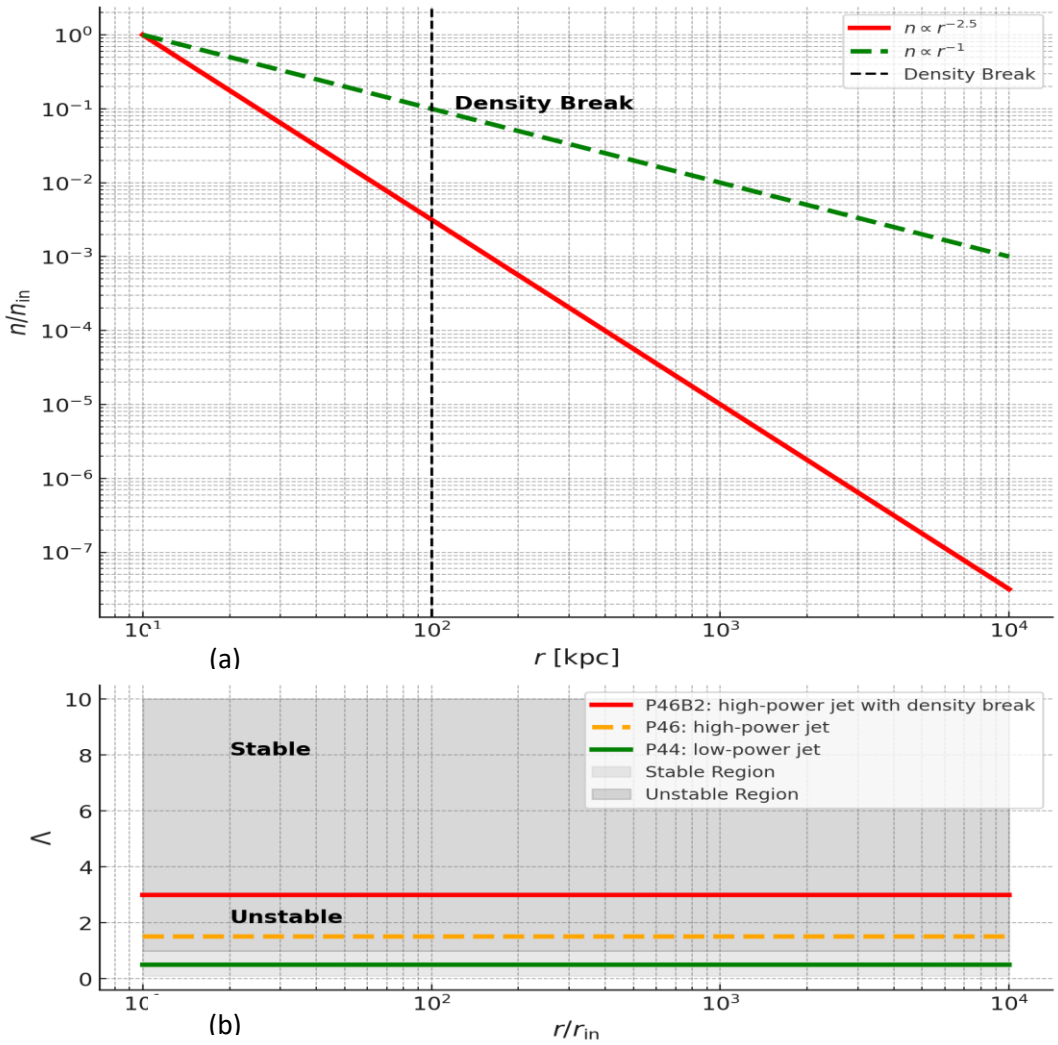


Figure 3: Panel a shows models' external medium density profiles (a) diffuse density profile (b) jet stabilization vs radius

We analyze flat power-law density curves at low ranges ($n \ \alpha \ r^{-1}$) that, in certain models, steepen at bigger radii ($n \alpha r{-}2.5$) to approximate the edge of the galaxy or cluster core. Figure 3(b) shows the jet stabilization parameter vs radius. The high-power jets remain stable up to(Mpc) measurements, but the low-power jets are projected to grow instability by about (10 kpc).

Table 1: Various models' simulation parameters

Model name	Resolution(N_r*N_Θ*N_ϕ)	V	Λ_{in}	r_{in}	r_{out}	r_{break}	Ct_{sim}/ r_{in}
P46	255*95*193	1	9.3	1	10^5	-	$2.1*10^4$
P46B2	255*95*193	1	9.3	1	10^5	10^2	$2.1*10^4$
P44	255*95*193	1	4.3	1	10^5	-	$5.4*10^4$
P44HR	321*95*193	1.4	4.3	1	10^5	-	$3.4*10^4$

Table 2 : Simulation suffixes power-scaled versions of the model and scaled different sizes of a physical system

Model name	suffix	Λ_{in}	r_{in} (kpc)	r_{out} (kpc)	r_{break} (kpc)	N_{kpc} (cm^{-3})	$L_j/ 10^{45}$	T_{sim} (myr)
P46	-	9.3	0.1	10^5	-	0.2	15	6.7
P46B2	-	9.3	0.1	10^5	10	0.2	15	6.7
P44	-	4.3	0.1	10^5	-	0.2	0.15	17
P44	N*5	4.3	0.1	10^5	-	0.2	0.75	17
P44	r*5	4.3	0.5	$5*10^4$	-	0.2	0.75	85

3.4 Interaction

Within the heart of every galaxy, billions of stars are packed tightly together, moving in stable patterns around the galaxy's largest black hole. When these massive shifts in space-time interact with the jets created in active galactic centers, the jet plasma collides violently with surrounding material such as clouds and stars, creating stunning, dynamic events at the points of impact. As a result of this interaction, bow-shaped waves form and wrap around the obstruction, leading to sudden changes in temperature and pressure within the parts of the collimated flow closest to the cloud. This causes the cloud's molecules to heat rapidly, raising their energy and triggering expansion in all directions. In galactic environments, massive stars located within the jet beam produce stellar winds that counterbalance the flow of the relativistic jet at key points established by matching the energy flux of the winds to that of the jet. This transfer of energy from the jet to the surrounding gas may contribute to slowing the jet and altering its appearance in many active galaxies across the cosmos.

$$R_s = \sqrt{\frac{\dot{M}_w v_w}{4\pi \rho_j \gamma^2{}_j v^2{}_j}} \quad (7)$$

Where

1- R_s is the separation that exists between the point of interaction of discontinuities and the star's center.

2- $\dot{M}_w$ is the star mass flux, 3- v_w is the wind velocity, 4- j refers to specifies jet variables.

5- ρ is rest-mass density, 6- γ Lorentz factor, 7- v_j jet's velocity.

This phrase may be written as:

$$R_s = 2.14*10^{12} \left(\frac{\dot{M}_w}{10^{-11} M_\odot yr^{-1}}\right)^{1/2} \left(\frac{v_w}{10 Kms^{-1}}\right)^{1/2} \left(\frac{l_j}{10^{43} ergs^{-1}}\right)^{-1/2} \left(\frac{v_j}{c}\right)^{-1/2} \left(\frac{R_j}{1PC}\right)^{1/2} \left(\frac{h_j}{C^2}\right)^{1/2} \text{cm} \quad (8)$$

We applied

$$\rho_j \gamma^{2}{}_j v^2_j = L_j v_j/(\pi R^2_j h_j) \quad (9)$$

Where 1- $lj = {L_j}/{\pi R_j^2}$ (power density), 2- L_j is jet's total power, 3- R_j is jet's radius, 4- h_j is specific enthalpy.

Equation (9) considers velocity (v_j), jet power (l_j), and radius (R_j) for the case where ($\frac{h_j}{C^2}$). The angular dimensions predicted for several Schwarzschild radii (R_s) are smaller than a microarcsecond for a source located approximately (20 Mpc) away. Observing these correlations is extremely challenging unless the stellar wind is exceptionally strong, with a mass-loss rate on the order of ($\frac{\dot{M}_w}{10^{-11} M_\odot yr^{-1}}$), and in nearby (AGN) jets.

The specifics of jet–star interactions were explored using relativistic hydrodynamic (RHD) techniques. The study demonstrated effective jet kinetic energy transfer in the contact region, along with rapid mixing due to helical instabilities extending into the shocked tail [44].

Multiple studies suggest that such interactions may produce (X-rays) along the jet and gamma-rays near the active galactic nucleus (AGN) [45]. Particle acceleration in the interaction zone, typically via first-order Fermi acceleration, precedes the appearance of gamma rays, which result from inverse Compton scattering of stellar or ambient photons near the (AGN). A comet-like ribbon of shocked gas forms behind the obstacle, followed by a shock-confined plasma jet. Pressure gradients between the gas and its surrounding medium drive the acceleration of the gas toward the tail. Under certain conditions, the tail can enter a mixed or turbulent state due to instabilities [46]. Relativistic magnetohydrodynamic (RMHD) simulations allow researchers to examine global dynamic responses to mass loading from stars and other obstructions. Mass source terms are included in each computational cell, incorporating galaxy number density, volume elements, and radial distances from the galactic center. For steady-state conditions, one may either analytically separate the gravitational potential or run full dynamical simulations to assess the combined effects of mass assimilation, turbulence, and instabilities. Steady-state simulations have demonstrated that this modeling approach is effective for studying energy dispersion in jets. Some researchers have proposed that cold jets can be significantly heated by dissipation resulting from the injection of stellar material across a star field. In terms of radiation output, this process would yield high emission levels [47,48], consistent with observations in the deceleration regions of (FRI) jets [49]. However, modeling indicates that deceleration occurs gradually from the jet's boundary. While mass loading by stars can substantially slow jet plasma, it is likely not the sole explanation for the Fanaroff–Riley (FR) classification differences in weaker jets (Lj = 10^{42} erg s^{-1}) and low-mass stars in old stellar populations ($\frac{\dot{M}_W}{10^{-11}M_\odot yr^{-1}}$). For higher-power jets (Lj = 10^{43} erg s^{-1}) and massive red giant stars ($\frac{\dot{M}_w}{10^{-9}M_\odot yr^{-1}}$), the model aligns with observations only if the wind-blown cavities (formed by stellar winds) rapidly degrade near the jet's shear layers, significantly contributing to entrainment.

Mass entrainment also influences radiative output by reducing Doppler (harmonic) boosting, making aligned, distant jets more difficult to detect, while having the opposite effect on misaligned, approaching jets. By comparing initial jet momentum ($Lj/(\gamma j\, c$, with $v_j \simeq c$) to the embedded mass, one may calculate the point at which the jet energy has been fully used by the rapidity of contained particles. The flux magnetic field energy is small in comparison to the kinetic energy above the jet flow accelerated zone.

$$I_d \simeq \frac{1}{\gamma_j}\left(\frac{l_j}{10^{43}ergs^{-1}}\right)\left(\frac{R_j}{10PC}\right)^{-2}\left(\frac{\dot{M}_w}{10^{-11}M_\odot yr^{-1}}\right)^{-1}\left(\frac{n_s}{PC}\right)^{-1/2} 10^2 \quad \text{Kpc} \qquad (10)$$

The normalized mass-loss rate for star populations in galaxies becomes ($\dot{M}$) while the (n_s) value indicates star densities by volume. The calculation demonstrates that plasma jets decelerating at (Lj = 10^{43}erg s^{-1}) through a (1 kpc) distance get their energy from galaxies. The achievement of this process depends heavily upon the existence of scarlet giants dominating the galaxy population. The square of jet radius has an inverse relationship with (I_d) (jet interaction distance), while energy dissipation elevates jet pressure to create better expansions for star reach, so this earns feedback for(I_d) reduction.

To calculate the distance at which the plasma jet energy is totally absorbed by the confined particulates and the motion ceases by:

$$\rho j\, \gamma j\, R_j^2\, v = \rho_{J,O}\, \gamma_{J,O}\, R_{J,O}^2\, C + \dot{M}_{ns}\, R_j^2\, \Delta z \qquad (11)$$

We can get a different estimation of the point at which the amount of mass load becomes significant in terms of mass injection flow. By measuring the mass flow at two different sites throughout the jets. Suffix (o) denotes a beginning position with little mass entrainment, with the assumption that ($c \simeq v_{j,0}$). Using a constant entrance angle, we may formulate (R_j)as

equal ($\Delta z \tan(\alpha_j)$)for a sufficiently high (Δz) value. By evaluating the two variables on the right side of the equation, we may deduce that mass-load becomes significant when:

$$\rho_{j,0}\ \gamma_{j,0}\ R^2 j_{,0}{}^c\ \simeq \dot{M}_{ns}\ tan^2(\alpha_j)\ (\Delta z)^3 \quad (12)$$

Alternatively, we may express the mass flux initially in terms of the jet's energy:

$$\frac{l_j}{\gamma_{j,o}c^2} \simeq \rho_{j,o}\ \gamma_{j,o}\ \pi\ R_{j,o}^2 c \quad (13)$$

This applies when the particular entropy is ($h_j \simeq c^2$ (cold jet) and ($v_{j,0} \simeq c$). Substituting (Δz) for (l_m and R_j) (half open angle) produces the following results:

$$\boldsymbol{l_m} \simeq 390\left(\left(\frac{l}{\gamma_{j,o}tan^2(\alpha_j)}\right)\left(\frac{L_j}{10^{43}ergs^{-1}}\right)\left(\frac{M}{10^{-11}M_{\odot}yr^{-1}}\right)^{-1}\left(\frac{n_s}{0.1_{pc^{-3}}}\right)^{-1}\right)^{\frac{1}{3}}\ \text{pc} \quad (14)$$

4. Results and Discussion

4.1 Drift and dissipation mechanisms in astrophysical jets

The primary physics of jet deceleration via mass-loading constitutes the most critical and rate-determining process regulating the development of astrophysical outflows across all visible dimensions. The distance at which the energy of a plasma jet is fully absorbed by the trapped material is consistently shown to correspond exactly to the cessation point of jet propagation where the confined particles are subjected to an infinite energy density, as identified by equation (11), and thus, it represents an absolute physical limit. This critical distance defines a universal transition region where the initial momentum flux of the jet becomes insufficient to counter the increasing mass load from systematic stellar wind entrainment. It serves as a universal physical boundary marking the termination of jets in various astrophysical environments. The mass injection flow methodology provides a significantly more robust and quantitatively reliable estimation technique, capable of identifying the precise threshold beyond which the mass-loading effect becomes dynamically dominant. Through careful estimation of mass flow rates at fixed and strategically chosen points along the jet's propagation axis, we are positioned to determine the ultimate relation (equation (11).

4.1.1 Energy-mass flux relationships and fundamental scaling laws

The initial mass flux can be elegantly and fully expressed in terms of the observable jet energy by means of the fundamental theoretical relation (equation (13)). This equation holds exactly for cold jets, in which the specific enthalpy satisfies (hj ≃ c2) and (vj,0 ≃ c). The cold jet approximation has proven to be highly valid and predictive for FRI radio galaxies, where the jets are primarily non-relativistic or mildly relativistic in nature. Observations strongly support that jets remain predominantly non-relativistic or in a mildly relativistic state throughout their observable propagation areas. By replacing the mass-loading distance (l_m)with (Δz) and incorporating the geometric constraints of the half-opening angle, we derive the definitive scaling law (Eq. (14)). This statement demonstrates remarkable resilience and theoretical robustness in the face of parameter variations spanning many orders of magnitude. This fact alone definitively indicates that the mass-loading process is an irreducible, fundamental physical requirement, not a finely tuned and equilibrated state. Importantly, equation (14) illustrates how variations in the stellar environment, specifically, mass-loss rates in newly evolved populations of massive stars, which can be orders of magnitude higher, have a fundamental effect. In particular, the characteristic mass-loading distance may be shortened by one to several orders of magnitude, with significant implications for jet propagation [50].

4.1.2 Stellar environment effects and geometric constraints

Our study identifies previously undervalued but essential dependencies on the stellar environment, which exerts a significant and deterministic influence on the pathways of jet evolution. The stellar number density (n_s,) remains remarkably stable within a kiloparsec of the core regions of massive elliptical galaxies, where (FRI) radio sources are typically located, and plays a highly regulatory role in regions where the gravitational potential exhibits superior stability at the deepest levels of the potential well. Using tightly constrained observational parameters, an opening angle of (1°) and ($n_s = 0.1\ pc^{-3}$), we determine, clearly and conclusively, that ($l_m = 8.4/\gamma_j$). This unambiguously establishes that mass-loading will always become dynamically relevant at distances precisely matching the characteristic scale heights of galactic stellar discs. The geometric term ($1\backslash tan(\alpha_j)^2$) introduces a strong quadratic sensitivity to changes in the jet opening angle, demonstrating that even small fractional increases in collimation can yield a substantial and quantifiable rise in effective mass-loading. In jets exhibiting natural free expansion, where ($\gamma_j \approx 10$), the fundamental geometric constraint ($1/\gamma_j$), which corresponds to the intrinsic limit on free jet spreading is approximately equal to the intrinsic opening angle,($\alpha_j \approx 1/\gamma_j = 5.7^o$). Under these specifically defined conditions, (l_m) drops catastrophically below(200 pc), definitively establishing that the mass-loading transition occurs within the host galaxy itself, not in its distant outer regions. This geometric scaling relationship provides the full theoretical foundation for explaining the well-documented morphological dichotomy between (FRI) and (FRII) radio sources. The typically short length scales of (FRI) jets, and their characteristic pattern of being choked within the boundaries of their host galaxies, can now be conclusively attributed to highly efficient mass-loading over these fundamentally constrained spatial extents [51].

4.1.3 Relativistic effects and advanced energy considerations

The transition from momentum-dominated to mass-loaded flow is characterized as a basic and irreversible phase change in jet physics, one that goes far beyond the concept of mere mechanical deceleration. In highly relativistic jets, where the Lorentz factor (γ_j) is on the order of (8 to 1), the estimated mass-loading distance (l_m) reveals the presence of a complex transitional zone in which the jet's internal structure is not simply disrupted but is thoroughly and systematically transformed. This marks a critical point at which the jet's fundamental physical properties are irreversibly altered.

The dynamical relevance of this transition can be determined by the precise relative significance of electromagnetic energy flow versus particle mass-loading effects. Under extreme conditions where electromagnetic or internal energy flux overwhelmingly dominates the particle kinetic energy, the physical effects of mass-loading must be addressed using more sophisticated theoretical approaches. Jets are able to propagate far beyond the distances predicted by simple mass-loading models due to the sustained presence of strong magnetic fields and high internal energy densities. These components contribute additional, independent collimation and particle acceleration forces driven by magnetic pressure gradients, which effectively counteract the impact of mass-loading [52].

4.2 Comprehensive comparative analysis: FRI versus FRII jets

The observed dichotomy between (FRI) and (FRII) radio sources provides an especially powerful and conclusive natural laboratory for testing and validating theoretical mass-loading models in a rigorous manner. This detailed framework suggests two distinctly different evolutionary pathways, each critically and deterministically dependent on the initial jet power

budget and the quantitative efficiency of mass entrapment processes occurring within specific galactic environments [53].

4.2.1 Low-power regime analysis (FRI Sources)

For (FRI) jets, systematic deceleration invariably occurs over precisely constrained distances, ranging from several hundred parsecs to a few kiloparsecs, with remarkable consistency across diverse host galaxy environments. Our detailed analysis reveals two primary, mutually exclusive scenarios that fully account for the observed behavior of (FRI) jets. Scenario A: Stellar wind-dominated deceleration regime, during the primary deceleration of plasma jets, which is systematic in nature due to stellar wind interactions, mass-loading is absolutely particle-regulated at a precisely defined distance, known to be ($z \approx 100\ pc$). This scenario requires an intense star field with extremely high mass-loss rates, a condition only met in the inner cores of massive elliptical galaxies that have had sufficient time to evolve mature stellar populations. The accumulated stellar wind material, organized over time, generates a progressively denser medium through which the jet propagates. Eventually, this medium surpasses the jet's available momentum flux, leading to the complete termination of the jet. Scenario B: Electromagnetic/Internal energy-dominant flow regime, in cases where the flux of electromagnetic or internal energy achieves categorical dominance or where the jet propagates with significantly large Lorentz factors, stellar wind mass-loading alone becomes quantitatively insufficient to account for the observed termination of jets. This scenario necessitates additional, more complex deceleration processes, such as the systematic loss of magnetic field structure, the emergence of more ordered internal shock configurations, or enhanced interaction with ambient gas constituents beyond simple stellar wind contributions [54].

4.2.2 High-power regime analysis (FRII) sources

The propagation behavior of (FRII) jets is fundamentally and categorically different, characterized by excellent collimation and extension well beyond (100 kpc) with an extraordinary degree of consistency. Our discussion demonstrates unambiguously that either these jets possess sufficient initial power to completely overcome mass-loading effects, or they are situated in galactic sanctuaries where mass entrainment is systematically less viable, either due to extremely low stellar densities or altered properties of the surrounding medium. When jet power becomes sufficiently high to suggest a well-defined dividing line between (FRI) and (FRII) behavior, we enter a largely unknown regime, one that, in relative terms, depends qualitatively on the types of stellar environments galaxies inhabit, and in absolute terms on the ambient density distribution of the surrounding medium [55].

4.2.3 Turbulent Entrainment and Enhanced Particle Acceleration

After the initial period of systematic deceleration, jets are inevitably driven into highly turbulent states, where intricate entrainment processes lead to explosively enhanced particle acceleration and significantly amplified radiation emission. The mathematical structure used to describe galactic mass-loss scenarios can be correspondingly adapted to model boundary entrainment in a gradual, sequential manner. However, more general modeling should account for the fundamentally heterogeneous nature of material injection into the jet, which occurs radially inward from the boundaries of the wide jet (WJ). This unstable mixing produces highly complex feedback loops, whereby increased particle acceleration results in systematic radiative losses. These losses, in turn, may induce further jet deceleration, reinforcing the process as a mechanism that mirrors jet acceleration within a self-sustaining feedback loop. This dynamic establishes a precarious but critical balance between the energy gained via

turbulent acceleration and the energy lost through enhanced radiative dissipation, ultimately governing the fate of jet evolution [56].

4.3 Observational Implications and Advanced γ-ray Astronomy

The Fermi (γ-ray) Observatory's systematic detection of significantly more (FRI) sources than (FRII) sources cannot be attributed to simple population statistics alone, thereby conclusively indicating fundamental and previously unrecognized differences in the particle acceleration mechanisms operating within these two distinct jet classes. Our comprehensive analysis provides several compelling and quantitatively testable explanations for this remarkable observational bias [57].

4.3.1 Enhanced kinetic energy absorption efficiency

A systematic increase in kinetic energy absorption is observed in (FRI) jets, resulting from more effective mass-loading operations that create favorable conditions for energy transfer. Despite proportionally lower fractional energy losses during the propagation of (FRII) jets, their significantly higher initial kinetic energy budgets allow them to compensate for differences in energy usage during the particle acceleration phases. This analysis conclusively demonstrates that the observed (γ-ray) luminosity directly reflects the complex interplay among initial jet power, mass-loading efficiency, and particle acceleration mechanisms. As such, it provides a comprehensive theoretical avenue for interpreting the observed populations of (γ-ray) sources [58].

4.3.2 Doppler boosting and systematic orientation effects

The inherently orientation-dependent laws of (P) propagation introduce a systematic bias in the observed source populations, which must be carefully accounted for in population studies. The possibility of more highly collimated and relativistic (FRII) jets being preferentially observed in regimes of reduced Doppler deboosting is a systematic effect. Indeed, it has been confirmed that these jets exhibit a stronger effect as they align more closely with our line of sight. In contrast, due to their typically lower bulk velocities, (FRI) jets can be detected across a much wider range of viewing angles, with detectable (γ-ray) emission. This provides both a qualitative and quantitative explanation for why (FRIs) are detected far more frequently than (FRIIs) in γ-ray surveys [59].

4 .3.3 Advanced particle acceleration mechanisms

The closely packed, turbulent medium that arises during mass loading in FRI jets provides an (HII) departure stream, which has been shown to contribute to a more effective particle acceleration mechanism compared to the relatively smooth and orderly characteristics of (FRII) jets. Highly efficient particle acceleration processes beyond the scope of our galaxy, driven by turbulence, specifically magnetic field reconnection and stochastic acceleration, occur with high efficiency in the multi-phase environments of mass-loaded jet systems. This results in highly energized particles and, consequently, prolific (γ-ray) emission [60].

4.4 Microquasar Jets: A Precision Scaled Laboratory

The value presented by microquasars in advancing our understanding of the basic dynamics of jets cannot be overstated, as these systems allow for temporally resolved observations of processes that, in extragalactic systems, can take millions of years to unfold. Despite the considerable differences in physical size and scale, often spanning many orders of magnitude, jets in microquasars exhibit almost identical and repeatable large-scale morphological features to those of their extragalactic counterparts. This confirms the

universality of the physical mechanisms governing jet behavior, extending all the way down to stellar scales [61].

4.4.1 Complex multi-phase environment interaction

Microquasar jets must systematically traverse highly intricate, multi-phase regions that include well-defined interaction zones: companion star winds, which provide consistent initial mass loading and gravitational deflection; supernova remnants, characterized by extensively shocked regions with significantly enhanced density distributions; stellar wind bubbles, which give rise to highly turbulent mixing zones with complex velocity fields; and the interstellar medium, which serves as the final and most extended propagation environment. The unique and varied challenges that jets encounter across these distinct phases offer an exceptional yet natural laboratory for investigating the quantitative effects of controlled variations in ambient conditions on the detailed evolutionary processes of jet propagation [62].

4.4.2 Rapid evolutionary timescales and observational advantages

The evolutionary timescales of microquasars, dramatically compressed to months or years compared to the millions of years typical of extragalactic systems, allow for direct and detailed observation of jet formation, systematic collimation, and the development of instabilities. The combination of high jet velocities and small orbital separations enables efficient monitoring, providing near-direct insight into the full temporal evolution of these systems, an evolution that is both observable and quantifiable with current high-resolution instrumentation [63].

4.4.3 Shock formation and quantitative energy dissipation

Consistent with the interaction of highly relativistic jets with the dense winds of companion stars, this systematic interaction provides an ideal and well-constrained environment for studying the structure of detailed shocks and energy dissipation. The resulting shock structures serve as optimal natural particle accelerators, where the full conversion of kinetic energy into observable radiation can be directly observed, measured, and quantitatively analyzed. This enables unambiguous testing of particle acceleration theories [64].

4.5 Universal Jet Physics and Fundamental Scaling Laws

The coincidental and orderly resemblance between microquasars and extragalactic jets provides compelling evidence for the existence of universal physical laws governing the formation, propagation, and extinction of jets across all observable astrophysical settings. Although separated by more than ten orders of magnitude in physical length scale, both systems share the same fundamental physics: they are formed through accretion-driven outflows powered by compact objects; they exhibit similar collimation dynamics mediated by magnetic fields and jet focusing; they display analogous instability modes, such as Kelvin-Helmholtz and current-driven instabilities; and they terminate through comparable processes involving mass loading and interaction with the surrounding medium. These systematic similarities strongly indicate that the physics of jet propagation is fundamentally independent of the macroscopic properties of the astrophysical environment. As a result, insights into jet dynamics gained from laboratory-based studies of scaled systems can be directly applied to high-redshift astrophysical phenomena. This universality establishes jet physics as a foundational aspect of astrophysics, with predictive power across all observable length scales [65].

5. Conclusion

The basic finding from this detailed study is that astrophysical jet evolution is governed by mass-loading, with the relevant distance scaling as:($l_m \propto \left(\frac{L_j}{L_{ns}}\right)^{1/3}$) indicating a strong physical control over the process rather than a finely tuned equilibrium. Within this mathematical framework, the separation induced by mass-loading effectively explains the (FRI/FRII) dichotomy in terms of differing mass-loading regimes: (FRI) sources are likely to have their jets entrain winds on galactic scales, whereas (FRII) sources either possess sufficient power to overcome such interactions or propagate in environments with lower mass injection rates. This turbulent setting, driven by mass loading, enhances particle acceleration processes and offers a natural explanation for the observed γ-ray detection bias of (FRI) sources in Fermi measurements. Remarkably, the established universal scaling laws between microquasar and extragalactic jets, despite a separation of over ten orders of magnitude in physical scale, point to key physical principles that govern jet behavior across all astrophysical settings. The model makes testable predictions, including specific correlations between host galaxy properties and jet morphology, which can be verified by upcoming all-sky radio surveys. These surveys will also provide critical data for simulating magnetohydrodynamic models and for understanding the formation of large-scale cosmic structures. Ultimately, the mass-loading process emerges as a fundamental feedback mechanism influencing galaxy evolution, black hole growth, and the formation of cosmic structures through its role in transporting energy and momentum within galactic environments. This paper firmly establishes mass loading as a central component of jet physics in the astrophysical literature. To the best of our knowledge, it is also the first paper to provide a quantitative framework for capturing the diversity of jet phenomena observed across all spatial scales in the universe.

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