Simulations of AGN-driven Galactic Outflow Morphology and Content

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Abstract

Using a series of 3D relativistic hydrodynamical simulations of active galactic nuclei (AGN) we investigate how AGN power, a clumpy interstellar medium (ISM) structure, and AGN jet angle with respect to the galactic disk affect the morphology and content of the resulting galactic outflow. For low-power AGN across three orders of magnitude of AGN luminosities ($10^{41} - 10^{43}$ erg s$^{-1}$) our simulations did not show significant changes to either the morphology or total mass of the outflow. Changing the angle of the AGN jet with respect to the galaxy did show small changes in the total outflow mass of a factor of 2–3. Jets perpendicular to the galactic disk created hot single-phase outflows, while jets close to parallel with the disk created multiphase outflows with equal parts warm and hot, and significant cold gas. Overall the final morphology of low-power AGN outflows depends primarily on how the jet impacts and interacts with large, dense clouds in the clumpy ISM. These clouds can disrupt, deflect, split, or suppress the jet, preventing it from leaving the galactic disk as a coherent structure. But for simulations with AGN luminosities $> 10^{42}$ erg s$^{-1}$ the ISM played a minor role in determining the morphology of the outflow with an undisturbed jet leaving the disk. The final morphology of AGN outflows is different for low-power AGNs versus high-power AGNs with the final morphology of low-power AGN outflows dependent on the ISM structure within the first kiloparsec surrounding the AGN.

Unified Astronomy Thesaurus concepts: AGN host galaxies (2017); Active galaxies (17); Fanaroff-Riley radio galaxies (526); Radio galaxies (1343); Hydrodynamical simulations (767); Astronomical simulations (1857); Relativistic jets (1390); Galaxy jets (601); Jets (870); X-ray active galactic nuclei (2035); Diffuse x-ray background (384); X-ray sources (1822)

1. Introduction

Active galactic nuclei (AGN) are important drivers of galactic outflows and are key components of galactic evolution. Astronomers are confident that AGN-driven outflows are generated by radiation pressure and mechanical energy from jets created around a central supermassive black hole (Begelman & Cioffi 1989; Bromberg et al. 2011; Tadhunter 2016; Harrison et al. 2018). The shape of the extended radio or X-ray emission from AGN-driven outflows is now generally agreed to be highly influenced by the local interstellar medium (ISM) on various spatial scales (Bromberg et al. 2011; Tadhunter 2016; Blandford et al. 2019; Hardcastle & Croston 2020; Patil et al. 2020), although there are suggested links between the AGN accretion mode and jet morphology (Best & Heckman 2012; Tadhunter 2016; Hardcastle 2018a). The diagnostic power of AGN-driven outflows has materialized in an ever-growing body of work using outflow properties to test AGN feedback (Harrison et al. 2018).

The fact that AGN-driven outflows possess a broad range of morphologies (e.g., Hardcastle & Croston 2020) presents a challenge for theorists. The content of AGN jets is still not well constrained, and models generally assume either an electron–position plasma, or an electron–proton plasma (Worrall 2009; Blandford et al. 2019). Along with the jet, multiple gas phases will be entrained in the outflow (An & Baan 2012; Morganti et al. 2013; Rupke & Veilleux 2013; Veilleux et al. 2013; Cicone et al. 2014; Harrison et al. 2014; Fiore et al. 2017; Harrison et al. 2018; Husemann et al. 2019b; Costa et al. 2020; Herrera-Camus et al. 2020; Comerón et al. 2021). Outside of the galaxy, warm and cool gas will also condense out of the hot halo when perturbed by shocks from the outflow (Gaspari et al. 2018). The plasma in the jet produces observable radio emission through synchrotron radiation (for a review see Blandford et al. 2019), while X-rays trace shocks and the hot outflowing gas (Longair & Willmore 1974; Hardcastle & Worrall 2000; Bicknell 2002; Birzan et al. 2004; Worrall 2009; Sambruna & Harris 2012; Hardcastle & Croston 2020). Observations have shown that most radio jets are surrounded by a cocoon or a shell of hot X-ray emitting gas (O’Dea et al. 2017; Maselli et al. 2018; Stuardi et al. 2018; Liao et al. 2020; Minsley et al. 2020; Jimenez-Gallardo et al. 2021; O’Dea & Saikia 2021).

The study of radio emission from active galaxies has a vast history. The emission can be classified based on the size and the shape of the spectral energy distribution (SED; An & Baan 2012; Patil et al. 2020; O’Dea & Saikia 2021). At the smallest spatial scales compact symmetric objects (CSOs) appear to represent the beginning of the evolution of AGN-driven outflows, with gigahertz-peaked spectrum (GPS) sources and compact steep-spectrum (CSS) sources representing their later evolution. At the largest spatial scales radio lobes can be classified as either Fanaroff–Riley (FR) type I or FR type II (Fanaroff & Riley 1974). FR I radio lobes appear as more compact with less well-defined jets. The outer lobes of FR I jets are also dimmer than that immediately around the AGN. FR II radio lobes have longer, more well-defined jets ending in bright hot spots that make up more than half of the total radio luminosity. A simple description would be that FR I are “center brightened,” while FR II are “edge brightened” (Mingo et al. 2019).
Is it not clear whether the ultimate morphology of the outflows are due to effects of the ≈ 1 kpc scale ISM structure of the host galaxy (De Young 1993; Bicknell 1995; Kaiser & Alexander 1997; Gopal-Krishna 2000; Leipski et al. 2006; Mingo et al. 2019) or to interactions with small scale structures (< 1 pc) and the environment around the supermassive black hole (REESS 1971; Hardcastle et al. 2007; Nenkova et al. 2008a, 2008b; Mingo et al. 2014). Surveys of FR I and FR II galaxies indicate that radio lobe morphology is independent of AGN accretion modes and instead dependent on the jet’s interaction with the larger environment (Gendre et al. 2013; Asmus 2019; Mingo et al. 2019; Gleisinger et al. 2020). But the specifics of these interactions on the lobes is still not well understood as this extends to objects with weaker and much less well-defined outflows.

Previous theoretical work has been motivated toward examining jets and cocoons across a range of AGN powers (Worrall 2009; Wagner et al. 2012; Matsumoto & Masada 2013; Massaglia et al. 2016; Bourne & Sijacki 2017; Weinberger et al. 2017; Ehliert et al. 2018; Mukherjee & Bicknell 2018; Massaglia et al. 2019; Komissarov & Porth 2021; Yates-Jones et al. 2021). Our work expands on this by modeling jets in a very nonhomogeneous environment. For this paper we investigate how a clumpy ISM, on a ∼1 kpc scale, affects the shape, kinematics, and content of such an AGN-driven galactic outflow. We explore a full range of jet inclination angles with respect to the galaxy disk to understand ISM interactions for very highly inclined AGN. We ran a series of 3D relativistic hydrodynamical simulations with the direction of the jet ranging from perpendicular to the galactic disk to parallel to the disk. Because of the clumpy ISM each jet angle impacts a unique part of the ISM, creating a set of different outflow morphologies. Our clumpy ISM allows for complex outflow morphologies, such as split flows, deflected jets, and asymmetric outflows. Similar simulations have been run in 2D (Saxton et al. 2005), in 3D with a nonuniform ISM and the AGN power near the historical dividing line between the FR I and FR II lobes (Sutherland & Bicknell 2007; Jeyakumar 2009; Gaibler et al. 2011), in 2D with a clumpy medium out to 60 kpc and a high-power jet (Tortora et al. 2009), in 3D with a clumpy ISM and high-power (> 10^{43} erg s^{-1}) AGN (Wagner & Bicknell 2011; Gaibler et al. 2012; Wagner et al. 2012; Mukherjee et al. 2016), and in 2D with high resolution (Musoke et al. 2020). All of the abovementioned simulations are on the level of the local galactic environment comprising the ISM out to a few kiloparsecs. There are also numerous simulations at much larger scales (> 100 kpc) examining jets in a cluster environment. These include hydrodynamic simulations in 2D and 3D (Krause 2005; Donohoe & Smith 2016; English et al. 2019; See et al. 2021; Smith & Donohoe 2021; Yates-Jones et al. 2021), magneto-hydrodynamical simulations in 2D and 3D (Mendygral et al. 2012; Hardcastle & Krause 2013, 2014; Weinberger et al. 2017), and semi-analytic models based on simulations (Turner & Shabala 2015; Hardcastle 2018b). Our simulations are commensurate with the former simulations of jets interacting with the local ISM and not the larger cluster medium. For a review of the simulations of jets see Marti (2019) or Komissarov & Porth (2021).

To test how a clumpy ISM affects the morphology of the outflow, we run a set of simulations ranging over AGN inclination angles of 0°–90° with \( P_{\text{AGN}} = 10^{42} \) erg s\(^{-1}\), and then a smaller set with angles of 30°–60° with \( P_{\text{AGN}} = 10^{43} \) and 10^{44} erg s\(^{-1}\). To investigate how the AGN power relates to the break between FR I and FR II we ran a set of simulations with the AGN power ranging from 10^{41} erg s\(^{-1}\) to 10^{46} erg s\(^{-1}\) to see how AGN power may affect the outflow morphology. In the radio, the traditional break between FR I and FR II is \( L_{150} \sim 10^{26} \text{WHz}^{-1} \) (Fanaroff & Riley 1974; Ledlow & Owen 1996; An & Baan 2012; Mingo et al. 2019). This corresponds to an AGN jet power of \( \sim 10^{42.5} \) erg s\(^{-1}\) (Willott et al. 1999; Ineson et al. 2017), which is spanned by the power ranges or simulations. Our full set of simulations with corresponding AGN inclination angles and powers is given in Table 1.

In Section 2 we explain our setup and how we generate the clumpy ISM. We use the same initial conditions for all simulations. In Section 3 we discuss how the direction of the AGN jet affects the overall morphology of the outflow. In Section 4 we discuss how the AGN jet power influences the morphology of the outflow. Then in Section 5 we describe how the outflow consists of two components, a relativistic jet with laminar flow and a turbulent semi-spherical bubble of hot gas. For \( P_{\text{AGN}} < 10^{43} \) erg s\(^{-1}\) the evolution of the jet and bubble components depends strongly on the interaction of the AGN jet with the ISM within the first kiloparsec. For \( P_{\text{AGN}} > 10^{44} \) erg s\(^{-1}\) the outflow is dominated by the relativistic jet with laminar flow.

### 2. Simulation Setup

We model an AGN-driven jet using the public Athena code (Stone et al. 2008). Because the AGN jet has a relativistic velocity we use the relativistic unsplit Monotonic Upstream-centered Scheme for Conservation Laws–Hancock (MUSCL–Hancock) integrator with the relativistic Harten–Lax–van Leer–Contact (HLLC) Riemann solver (Mignone & Bodo 2005) included with Athena. The code has been modified (Tanner et al. 2016) to include radiative cooling down to 10 K, using a cooling function that combines the function given by Koyama & Inutsuka (2002) with tabulated solar metallicity data from Sutherland & Dopita (1993).

We set up a computational space of 5000 × 5000 × 8000 pc divided into a grid of 500 × 500 × 800 cells giving us a resolution of 10 pc per cell.

In our simulations we tilt the direction of the AGN jet with respect to the vertical (minor) axis of the galaxy. Possible values range from between 0° (perpendicular to the disk) to 90° (parallel to the disk). We also vary AGN luminosities over six orders of magnitude from 10^{41} erg s\(^{-1}\) to 10^{46} erg s\(^{-1}\). The combinations of AGN luminosities and tilt angles we use are given in Table 1 for a total of 19 simulations. Each simulation is run for a total of 600 kyr at which point in all but two simulations the jets have reached the edge of the computational grid.

| AGN Power (erg s\(^{-1}\)) | Angles |
|-----------------------------|--------|
| \( 10^{41} \)             | 30°, 45°, 60° |
| \( 10^{42} \)             | 0°, 15°, 30°, 45°, 60°, 75°, 90° |
| \( 10^{43} \)             | 30°, 45°, 60° |
| \( 10^{44} \)             | 30°, 45° |
| \( 10^{45} \)             | 30°, 45° |
| \( 10^{46} \)             | 30°, 45° |
2.1. Initial Galactic Disk

We model the gravitational potential with two parts consisting of a spherical stellar bulge and a stellar disk. Because we are modeling only the central few kiloparsecs we chose not to include the dark matter halo as at this range it would not significantly affect the dynamics of the gas.

The spheroidal bulge \( \Phi_{\text{bulge}}(R) \) is modeled as a King model,

\[
\Phi_{\text{bulge}}(R) = -\frac{GM_{\text{bulge}}}{r_0}\left[\ln(\frac{R}{r_0}) + \frac{1 + (\frac{R}{r_0})^2}{\frac{R}{r_0}}\right],
\]

with \( R = \sqrt{r^2 + z^2} \), radial scale size \( r_0 \), and mass \( M_{\text{bulge}} \). The disk is modeled as a Plummer–Kuzmin potential (Miyamoto & Nagai 1975)

\[
\Phi_{\text{disk}}(r, z) = -\frac{GM_{\text{disk}}}{\sqrt{r^2 + (a + \sqrt{z^2 + b^2})^2}}.
\]

The total potential is

\[
\Phi_{\text{tot}} = \Phi_{\text{bulge}} + \Phi_{\text{disk}}.
\]

For our simulations we set the values for the mass and scale lengths as shown in Table 2.

We model the initial gas density as a two-phase medium with a hot diffuse halo and a cool disk. We use the total gravitational potential given in Equation (3) to set the density of the smooth halo using,

\[
n_{\text{halo}}(r, z) = n_{\text{halo}}(0, 0) \times \exp\left[-\frac{\Phi_{\text{tot}}(r, z) - \Phi_{\text{tot}}(0, 0)}{\epsilon_{\text{h},\text{halo}}}\right],
\]

The cool disk gas is set similarly, but includes terms for rotation

\[
n_{\text{disk}}(r, z) = n_{\text{disk}}(0, 0) \times \exp\left[-\frac{\Phi_{\text{tot}}(r, z) - \epsilon_{\text{disk}}(r, 0) - \epsilon_{\text{disk}}^2(0, 0)}{\sigma^2 + \epsilon_{\text{disk}}^2}\right],
\]

where \( n(0, 0) \) is the central density, \( \sigma, \epsilon_{\text{disk}} = \sqrt{k_B T_{\text{disk}}/m_H} \) the sound speed, and \( \epsilon_{\text{disk}} \) is the ratio of azimuthal to Keplerian velocity. The smooth density distribution of the disk is multiplied by a fractal distribution generated using the publicly available code pyFC written by Alex Wagner.\(^1\) We apply a tanh profile to both the vertical and radial directions to constrain the disk with scale lengths of 1000 pc and 3000 pc, respectively.

This prevents a nonphysical disk profile at large radii as mentioned in literature that used similar methods (Cooper et al. 2008; Tanner et al. 2017; Mukherjee & Bicknell 2018). The disk density is then scaled to an average density of 10 cm\(^{-3}\). This gives a total gas mass of \( \sim 8 \times 10^6 M_\odot \) and a column density of between \( 10^{22} \) and \( 10^{24} \) particles cm\(^{-2}\). For our initial conditions, the disk gas is set to a temperature of \( 10^4 \) K, and the halo gas to \( 5 \times 10^6 \) K. However, the clumpy disk gas quickly cools to the density-dependent equilibrium temperature based on the radiative cooling function used. Figure 1 shows an XZ slice of the initial gas density.

![Figure 1. XZ slice showing the initial density in particles cm\(^{-3}\). The computational domain covers 5000 \( \times \) 5000 \( \times \) 8000 pc divided into a grid of 500 \( \times \) 500 \( \times \) 800 cells.](image)

2.2. AGN Jet

At the center of the computational grid all cells within a radius of 100 pc are reset at each timestep to their initial state. This effectively acts as an inner boundary condition on the grid. With our resolution the AGN region has a diameter of 20 cells, sufficient to resolve the jet cone, but not to resolve the gaseous torus around the central black hole. Therefore we make no assumptions about the gaseous torus. Inside the AGN region we generate a biconical outflow with an opening angle of \( 20^\circ \), based observationally on the median opening angle for a large sample of Monitoring Of Jets in Active galactic nuclei with VLBA Experiments (MOJAVE) AGN (Pushkarev et al. 2017). The direction of the outflow can be tilted with respect to the vertical axis with \( 0^\circ \) being directed vertically out of the galaxy and \( 90^\circ \) directed horizontally into the plane of the disk.

Using the method employed by Wagner & Bicknell (2011), Mukherjee et al. (2016), and Mukherjee & Bicknell (2018), which is based on Bicknell (1995), we set the pressure \( (p) \) and

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\(^1\) https://pypi.python.org/pypi/pyFC

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Table 2

| Constant | Value |
|----------|-------|
| \( M_{\text{bulge}} (M_\odot) \) | \( 4.0 \times 10^9 \) |
| \( M_{\text{disk}} (M_\odot) \) | \( 1.0 \times 10^9 \) |
| \( \epsilon_{\text{disk}} \) | 0.95 |
| \( r_0 \) (pc) | 350.0 |
| \( a \) (pc) | 150.0 |
| \( b \) (pc) | 75.0 |
| \( \Gamma \) | 5.0 |
| \( \chi \) | 5.0 |
For purposes of this paper, Hot hard X-ray bands do not necessarily correspond to other traditional uses of soft, medium, and band. These are for convenience in tracking different parts of the hot gas, but do not necessarily correspond to other traditional uses of soft, medium, and hard X-ray bands.

| Name   | Temperature Range       |
|--------|-------------------------|
| Cold   | < 100 K                 |
| Warm   | 1000–5000 K             |
| Hot    | 5000–4,000 K            |
| Hot_X  | 0.5–3.0 keV             |
| Hot_XX | 3.0–10.0 keV            |
| Hot_XXX| > 10 keV                |

**Note:** For purposes of this paper, Hot_X is hot gas in our soft X-ray band, Hot_XX is hot gas in our medium X-ray band, and Hot_XXX is hot gas in our hard X-ray band. These are for convenience in tracking different parts of the hot gas, but do not necessarily correspond to other traditional uses of soft, medium, and hard X-ray bands.

Simulations with $P_{\text{AGN}} = 10^{42}$ erg s$^{-1}$. At higher angles of inclination the jet will have to pass through a longer column of disk gas, which significantly affects the shape and content of the outflow. But we also find that the immediate structure of the ISM within 1 kpc of the AGN has as strong an effect on the outflow as the angle of jet inclination. While it is more common for AGN jets to be roughly aligned with the minor axis of the host galaxy (Best et al. 2005; Lagos et al. 2011; Best & Heckman 2012; Heckman & Best 2014), there are some jets that are highly inclined with respect to the galactic axis (Kinney et al. 2000; Pringle 2003; Husemann et al. 2019a; Kamali et al. 2019).

In our simulations within a few hundred parsecs the jet forms an elongated cocoon of shocked jet gas surrounded by shocked ISM gas. The surrounding ISM pressure quickly collimates the jet, creating a region of high-velocity laminar flow. This action is in agreement with more idealized jet models developed by Bromberg et al. (2011) and more recently by Irwin et al. (2019).

At higher inclinations the jet must push through a longer ISM column requiring more energy and time before breaking out of the disk. As can be expected, and as shown in Figure 2, after 600 kyr, for all angles between 0° and 45° either the jet or the mixed ISM jet gas has cleared the disk and reached the computational domain. For higher angles the jet has not left the disk, though the expanding shocked ISM gas has escaped the disk. At 90°, with the jet directly into the disk, we did not expect the jet to leave the disk, but hot buoyant bubbles of shocked ISM gas have managed to expand outside of the disk. Husemann et al. (2019a) observed such a galactic outflow, with the AGN jet directed nearly parallel with the disk. The AGN dominated the central ~1 kpc and drove a multiphase outflow similar to a starburst-driven outflow (Tanner et al. 2017).

While the inclination of the jet does dominate the evolution of the low-power jet, with more highly inclined jet angles creating smaller outflows, there are a few interesting variations as part of this general trend. For example, with the jet at 75°, part of the jet is deflected downward $\approx 80°$ from the original jet direction by a large, dense cloud (Figure 2; 75°). This makes the outflow extremely asymmetric. To approximate the soft X-ray emission we calculate the energy flux from each cell using the radiative cooling function for cells with a temperature in the Hot_X range. This helps us trace the expected soft X-ray emission from the shells of hot gas surrounding the jets and from shock-heated ISM gas in the disk. While there is X-ray emission on both sides of the galaxy (Figure 3; 75°), only the bottom side would have gas traveling with high enough velocity to generate significant synchrotron radio emission. Due to the deflected jet, a larger X-ray bubble is formed than compared to those formed with the jet at 60° (see Figure 3; 60° and 75°).

At 30° the jet in both directions encounters dense clouds and does not have a clear path out of the disk (Figure 2; 30°). This causes the jet on the bottom side of the galaxy to deflect slightly, but on the top side the jet barely penetrates the edge of the disk. This contrasts with the jet at 45° which manages to bypass the same clouds that stopped the jet at 30°. While a jet angle at 30° has a shorter path out of the disk, the jet at 45° forms larger X-ray bubbles, as seen in Figure 3.

To understand how the velocity differs for the temperature ranges we calculate an escape velocity for each cell in the simulation using the gravitational potential (Equation (3)). We

$$p = P_{\text{AGN}} \frac{\gamma - 1}{\gamma} 1 \frac{1}{A \Gamma^2 (\gamma - 1) / \epsilon (1 + (\gamma - 1) / \gamma)}$$

and

$$\rho = \rho \chi \frac{\gamma - 1}{\gamma - 1}.$$
then bin the cells according to their velocity and sum up the mass in each velocity bin, separating the mass by temperature using the temperature ranges given in Table 3. Then we sum the mass for all cells with a velocity above the escape velocity for that cell. In Figure 4 we show the total mass in each temperature range at 600 kyr with respect to the AGN tilt angle. Then in Figure 5 we show how the outflowing mass above the escape velocity changes over the course of the simulation.

As shown in Figure 4 for all AGN angles the total outflow mass at 600 kyr is of the same order of magnitude between $10^8 - 10^9 M_\odot$, with the highest values at angles 30°–60°. In our simulations the total initial gas mass is $\approx 9 \times 10^9 M_\odot$. Thus at 600 kyr between 0.1% and 1.0% of the total initial gas mass has a velocity above the escape velocity. Whether this gas is completely removed from the galaxy and galactic halo will depend on factors such as the circumgalactic environment outside of our simulations.

As can be seen Figure 4, for simulations with shallow angles of inclination (> 95%) the total mass of the outflow is Hot$_{hX}$ (> 10^8 K). While for higher angles of inclination the Hot$_{hX}$ band makes up a smaller fraction of the gas above the escape velocity. At 90° the mass of the Hot$_{hX}$ gas is of the same order of magnitude with H$\alpha$ emitting gas. Also at all angles the cold and warm gases make up $\lesssim 1\%$ of the total outflow mass, but with an increasing AGN angle the total amount of the cold and warm gas mass increases by two orders of magnitude. In Figure 5 we show that the cold, warm, and H$\alpha$ emitting gas tend to decrease over time as they are shock heated, with a corresponding increase in hot gas (both Hot$_{sX}$ and Hot$_{hX}$).

In Figure 6 we plot the probability distribution functions (pdf) of mass versus outflow velocity for all angles at 600 kyr. In the graphs we set $v = 0$ km s$^{-1}$ (indicated by a vertical line) to the escape velocity calculated for each cell. To the right of the vertical line is the mass above the escape velocity and to the left is the mass below the escape velocity. In all cases the Hot$_{hX}$ gas dominates the high speed outflows. As shown in Figure 4, at higher angles the total outflow mass for both the H$\alpha$ emitting and Hot$_{hX}$ gas may be approximately the same order of magnitude, but as seen from Figure 6 the Hot$_{hX}$ gas consistently has a much higher velocity.

We do see the same behavior as shown in Figure 5 with the outflow becoming more multiphase at higher angles of AGN inclination. By looking just to the left of the vertical lines in Figure 6 we see a significant amount of cold and warm gas just

Figure 2. XZ slice showing the density in particles cm$^{-3}$. Each panel shows the density after 600 kyr for simulations with $P_{\text{AGN}} = 10^{42}$ erg s$^{-1}$. The top row shows AGN jet inclinations of 0°, 15°, and 30°. The bottom row shows AGN jet inclinations of 45°, 60°, 75°, and 90°.
below the escape velocity. This gas consists of dense clouds still moving upward but will most likely dissipate before reaching the circumgalactic medium (CGM). If we just consider the gas with velocities around the escape velocity then for all angles $m_{\text{Hot}} \approx m_{\text{cold}}$ and $m_{\text{Hot}} \approx m_{\text{H4}}$.

As shown in Figures 5 and 6 the angle of inclination does not significantly affect the total mass in the outflow, but it does significantly affect the composition of the outflow. Higher angles of inclination have a more multiphase outflow. This is because at lower angles the outflow is dominated by the hot,
momentum-driven jet, while at higher angles it is dominated by the pressure-driven, shocked ISM gas mixed with jet gas. Thus the pressure-driven bubbles are much more efficient at lifting cold gas off of the disk than the momentum-driven jets.

4. AGN Power

It is logical to assume that the AGN power should determine the morphology of the resulting outflow. More powerful AGNs do produce more extensive jets (for example, O’Dea & Saikia 2021). But based on our results in Section 3 we found that for low-power AGNs the ISM can significantly affect the morphology of the outflow. To determine how the AGN power affects the morphology of the galactic outflow we now look at simulations with $P_{\text{AGN}}$ ranging over six orders of magnitude. This covers a range of AGNs from Seyfert galaxies to quasar galaxies.

In Figure 7 we show XZ slices of the density for simulations with an AGN inclination of $30^\circ$ and powers ranging from $10^{11}$ erg s$^{-1}$ to $10^{16}$ erg s$^{-1}$. For $P_{\text{AGN}} < 10^{14}$ erg s$^{-1}$ the ISM acts as a significant barrier to creating a free-flowing outflow. Even after 600 kyr, there are still dense clouds in the path of the jet significantly disrupting the outflow. But for $P_{\text{AGN}} > 10^{15}$ erg s$^{-1}$ these clouds have been cleared from the path of the jet and have almost entirely dissipated into the hot bubble of the outflow.

In Figure 8 we show the same thing as in Figure 7 except with an AGN inclination angle of $45^\circ$. As before for $P_{\text{AGN}} < 10^{14}$ erg s$^{-1}$ the ISM acts as a significant barrier to creating a free-flowing outflow. For the simulation with $P_{\text{AGN}} = 10^{14}$ erg s$^{-1}$ the jet has managed to clear a path out of the top of the galaxy but not through the bottom.

To understand why this is we will consider a simple order of magnitude calculation to derive the energy input needed for a jet to clear a pathway through the ISM. Assuming a coupling efficiency of $\sim 5\%$ over the 600 kyr of the simulation an AGN with $P_{\text{AGN}} = 10^{14}$ erg s$^{-1}$ should contribute $\sim 10^{56}$ ergs to the ISM. If we consider the column of ISM gas within 300 pc of the center line of the jet through the disk, the total mass in this column has a maximum value of $\sim 10^5 M_\odot$ with a minimum of $\sim 10^4 M_\odot$ depending on the distribution of dense clouds in our simulations. The energy required to lift $\sim 10^5 M_\odot$ off of the disk and out of the gravitational potential of the host galaxy is $\sim 10^{56}$ ergs for the galaxy mass, as given in Table 2. With the exception of the AGN inclination angles $\sim 90^\circ$, $\sim 10^{56}$ ergs can be considered a practical upper limit on the total energy needed by an AGN to clear a path through the ISM.

This means that for almost all AGNs with $P_{\text{AGN}} > 10^{14}$ erg s$^{-1}$ the jet will impart enough energy to the ISM to remove all of the gas along the path of the jet regardless of the ISM structure. For AGNs with $P_{\text{AGN}} < 10^{14}$ erg s$^{-1}$ whether or not the jet can clear a path will depend on the structure of the ISM, the total gas mass along the path of the jet, and the temporal duration of the jet. For a lower-power AGN to clear a path through the ISM it must last for longer than the 600 kyr considered in our simulations. Such a case has been considered by Cecil et al. (2021) in simulating the Fermi bubbles in the Milky Way and in NGC 1068. In their simulations they assumed an intermittent AGN with $P_{\text{AGN}} = 10^{41}$ erg s$^{-1}$ lasting for 8 Myr. With a total energy input of $\sim 10^{55}$ ergs the AGN jet considered by Cecil et al. (2021) would be sufficient to clear a path through all but the densest ISMs.

5. Jets and Bubbles

On the simplest level the outflows have two components:

1. a high-velocity ($>0.1c$) momentum-driven jet of gas with smooth, laminar flow
2. a lower velocity, turbulent bubble of pressure-supported expanding hot gas consisting of mixed ISM and jet gas.

The growth of the high-velocity jet depends on its interaction with the ISM. If the jet has a relatively free path through low-density voids in the ISM then it forms a well-collimated laminar
outflow, surrounded by a turbulent cocoon. If a sufficiently large cloud is in the path of the jet then the jet can deflect, split, or stop it altogether. For the pressure bubble, any interaction with the dense ISM drives the growth of the hot, turbulent bubble surrounding the jet. The dense ISM significantly decreases the velocity of the jet gas and causes instabilities to grow in the turbulent mixing region surrounding the high-velocity gas.

In Figure 9 we show the magnitude of the vorticity, or curl ($\omega = \nabla \times v$), of the gas in the XZ plane at 500 kyr. The boundaries of the high-velocity jets can be clearly seen due to the large velocity difference with the surrounding gas, resulting in high values for the magnitude of the curl. Surrounding the high-velocity jets is the turbulent bubble, with a thin shell (< 100 pc) at the shock front of the expanding bubble.

With the AGN angle at 30° the laminar part of the outflow fails to leave the galactic disk because of interactions with the dense ISM. With a slight shift to 45° the jet bypasses the clouds that disrupted the jet at 30°. Because the jet at 45° still interacts with the same clouds, the hot turbulent bubbles for both 30° and 45° are still approximately the same size after 500 kyr.

**Figure 5.** Mass above the escape velocity in different temperature bands. The temperature bands can be found in Table 3. The lines show the escape mass for simulations with a luminosity of $10^{42}$ erg s$^{-1}$. Simulations with luminosities of $10^{41}$ erg s$^{-1}$ and $10^{43}$ erg s$^{-1}$ are shown with circles and crosses respectively. The markers are colored according to the emission band. The other graphs show how the mass above the escape velocity changes during the simulation time. In some of the simulations at certain timesteps there was no cold gas above the escape velocity. In the graphs above this is the reason for the vertical lines in the cold gas.
After escaping the disk, the shock front of the momentum-driven jet moves with a velocity of 30,000–60,000 km s\(^{-1}\) (0.1–0.2 \(c\)), while the pressure-driven bubble expands in all directions with a velocity of 3000–5000 km s\(^{-1}\). The exact speed of the shock fronts depends on how much of the dense ISM the jet interacted with. In Figure 10 we plot how the momentum-driven jets are coincident with the shocked ISM gas showing areas of high velocity (>0.1 c) and areas of high pressure. These are areas where we would expect the most radio and X-ray emission. Because our simulations do not include magnetic fields, and our grid resolution is too large to resolve the scale at which synchrotron radiation is generated, we can only make assumptions about where radio emission will be generated. In this case we assume that synchrotron radiation will be produced inside the high-velocity (>0.1 c) jets and inside the hot bubbles where the turbulent cascade will generate turbulence below the resolution of our simulations.

In Figure 10 we show three simulations for three AGN angles (30°, 45°, and 60°) and also three different AGN jet powers (10^{41} erg s\(^{-1}\), 10^{42} erg s\(^{-1}\), and 10^{43} erg s\(^{-1}\)). In simulations where the jet interacts more with the ISM there is significantly more shocked gas than in simulations where the jet has a relatively free path. For the AGN angle of 30° the jets on both sides are split and are beginning to dissipate into the

Figure 6. Probability distribution functions of the mass with respect to the escape velocity in simulations with \(P_{\text{AGN}} = 10^{42}\) erg s\(^{-1}\). The vertical line at 0 km s\(^{-1}\) is the escape velocity of the gas. To the right of the line is gas above the escape velocity, and to the left is gas below the escape velocity. The peak in each graph corresponds to the rest frame of the galaxy. This shows the state of the gas at 600 kyr. Binning is cut off at 20,000 km s\(^{-1}\).
turbulent bubble. The velocity and density difference will strongly contribute to Kelvin–Helmholtz instabilities in the less dense jet gas. The resulting turbulence induces strong shocks in the ISM as shown in Figure 10.

While there are noticeable differences as the AGN power increases, the strong similarities demonstrate that the structure of the ISM within the first ∼1 kpc dominates the evolution of the jet and the shape of the outflow. The angle of impact of the jet on the closest dense clouds determines whether the jet will remain laminar or if Kelvin–Helmholtz instabilities along with shocks will disrupt the jet before leaving the disk.

If there is a sufficiently dense cloud (>100 cm⁻³) of sufficient size (>50 pc) and mass (∼10⁶ M☉) located along the center line of the jet, the flow of the hot gas will split and the jet will become turbulent within a few kiloparsecs. This is the case with our simulations at 0°, 30°, and 60° shown in Figure 9. If the cloud is not along the center line of the jet but still in the collimated flow then a portion of the jet will split off as can be seen in our simulations at 45° and 75° in Figure 9.

For all AGN inclination angles the jet has a relatively significant interaction with the ISM, with the exception of 15° which had an unobstructed path on one side of the disk. As we show in Figures 10 and 11 only the simulation at 15° shows a jet exiting the bottom side of the disk with little disruption to the jet. Thus with a clumpy ISM a jet is more likely to interact with multiple significant density gradients on its way out of the galactic disk. This will contribute to jet disruption and the growth of the turbulent bubble surrounding the jet.

The downward jet in our simulation with an AGN inclination angle of 15° manages to reach the edge of the computational grid after 150 kyr while all other simulations that do reach the edge do so between 300 kyr and 500 kyr. Thus the ISM within the first kiloparsec has a significant effect on the speed of the jet-driven forward shock.

6. Discussion

As mentioned in Section 2 we are investigating how the ISM determines AGN-driven galactic outflow morphology across
six orders of magnitude of AGN jet power. The AGN powers considered straddle the traditional break point between FR I and FR II morphologies. Most of our simulations are the low-power analogs of the high-power AGNs in a clumpy medium modeled by Mukherjee et al. (2016) and Mukherjee & Bicknell (2018). Because we used the same randomly generated ISM for all our simulations we could compare how the angle of inclination and the AGN power affected the morphology of the outflows versus a clumpy ISM structure. While the physical size of our simulations does not encompass the physical sizes of typical FR I and FR II radio lobes, our simulations do provide insight into the initial growth and structure of AGN-driven galactic outflows in the first few kiloparsec. We find that for low-power AGNs the structure of the ISM can have a significant impact on whether a jet will form a coherent, laminar outflow or if the jet will be significantly suppressed, disrupted, split, or deflected in some way. But the importance of the ISM structure is greatly reduced for higher power AGNs. Between $10^{42} - 10^{45}$ erg s$^{-1}$ the power input of the ISM becomes sufficient to fully disrupt the ISM regardless of the presence of massive ($\sim 10^7 M_\odot$) ISM structures in the path of the jet. Above this break point the AGN jets will always form coherent, laminar outflows. We do not consider the impact of the cluster environment as it is outside the physical domain of our simulations. The various outflow morphologies seen in our simulations correspond to a variety of asymmetric or otherwise disrupted radio lobes observed in nearby galaxies.

In Figure 12 we show examples of the different morphology types found in our simulations of low-power ($P_{\text{AGN}} = 10^{42}$ erg s$^{-1}$) AGN jets. For the first few hundred parsecs, after an initial expansion, the AGN jet forms a collimated flow similar to the jet propagation model of Bromberg et al. (2011). A cocoon of shocked ISM gas surrounds the largely undisturbed laminar flow of the jet. At this point any radio emission would form a compact source object (CSO).

An unimpeded jet, or a jet through a uniform ISM, would form an elongated momentum-driven jet, as in Figures 12 (c) or (f). There would be a narrow cocoon of mixed ISM and jet gas surrounding it which will expand at much slower velocities than the forward shock of the momentum-driven jet. An undisrupted
jet, such as the one found in our simulation with an AGN inclination angle of 15°, will produce few shocks and a less prominent turbulent cloud surrounding the jet. As seen in Figure 11 (center image) there is very little shocked gas below the disk surrounding the jet. And in Figure 3 (top, center) there is negligible soft X-ray emission compared to the other simulations. Thus the momentum-driven jet is surrounded by a thin layer of hot X-ray emitting gas with a very small turbulent bubble around it.

Other possible configurations shown in Figure 12 include a split jet (e), a disrupted/deflected jet (c) and (f), and a suppressed jet (d). If the dense clouds are not directly along the center line of the jet then you get the case shown in Figure 12(e), where shock fronts will form around the clouds but the jet will not be significantly disrupted. But because the clouds still interact with the jet the turbulent bubble will contain more mixed ISM and jet gas. The clouds may also deflect the jet, as in (c), or may stop it all together as in (d).

Shells of hot X-ray emitting gas from the jet–ISM interaction have been observed in many galaxies with CSS/GPS sources, or large symmetric objects (LSOs; Kraft et al. 2005; Lanz et al. 2015; O’Dea et al. 2017; Maselli et al. 2018; Stuardi et al. 2018; Liao et al. 2020; Minsley et al. 2020; Jimenez-Gallardo et al. 2021). Using Chandra, Kraft et al. (2005) observed a hot shell of shocked gas surrounding the radio lobes in Centaurus A. This, they concluded, came from the jet–ISM interaction and is similar to the shocked shells in our simulations. In M 87 Kraft et al. (2005) observed three expanding shells of hot gas that they interpreted as coming from three separate AGN events. The radio lobes in M 87 are coincident with the X-ray cavities created by the youngest of these events. They also noted a fragmentation, or bifurcation, in the shocked ISM material lifted up by the jet. These kinds of filamentary structures are consistent with the complex shock fronts and entrained ISM gas as seen in Figures 10 and 11.

Figure 9. The magnitude of the vorticity for simulations with $P = 10^{42}$ erg s$^{-1}$ in the XZ plane at 500 kyr. Each simulation has a turbulent cloud that escapes the disk, but not all have a laminar jet escaping the disk. With a jet angle at 30° the jet is blocked on both sides by dense clouds, but at 45° the jets miss the clouds and escape the disk. At 75° a jet is deflected downward.
Optical spectroscopy of CSS radio sources have found Doppler shifted emission lines consistent with jet–ISM interactions of multiple components (O’Dea et al. 2002; Hekatelyne et al. 2018; Husemann et al. 2019a, 2019b; Hardcastle & Croston 2020; Luo et al. 2021). The velocities observed (a few hundreds km s$^{-1}$ to $\sim$1000 km s$^{-1}$) are consistent with the measured velocities of the cold components of our simulations (see Figure 6). In young jets only the hot and warm gas have had time to accelerate, while the cold gas takes time to accelerate up to terminal velocity (Santoro et al. 2018).

Finally there is the possibility of the significant deflection of a jet, as seen in the simulation at 75°. In that case the jet was deflected downward at an angle of $\sim$80° with respect to the original jet direction. AGN jet deflections of this type have

**Figure 10.** Images show the velocity (reds) in units of c, and pressure (blue–green–yellow) in code units. The range in pressure was chosen to highlight the strongest shocks. Only velocities above 0.1 c are shown. From left to right the AGN power is $10^{41}$ erg s$^{-1}$, $10^{42}$ erg s$^{-1}$, and $10^{43}$ erg s$^{-1}$. From top to bottom the inclination angles are 30°, 45°, and 60°. All simulations are shown at 600 kyrs.
been observed (Leipski et al. 2006; An et al. 2010). In the case of IC 2746 and ESO 428-14 (Leipski et al. 2006) at ≈ 2500 pc and ≈ 500 pc from the central black hole, respectively, there is a radio bright spot where the jet runs into a massive cloud in the ISM and the jet is redirected to nearly perpendicular to the original jet direction. In the case of Mrk 573 and Mrk 1014 the jets have not been deflected but have been stopped and confined in the galactic disk. We assume that whether a jet gets deflected, split, or stopped will depend on the total mass of the cloud and the geometry of the jet–cloud interaction.

An idealized outflow setup assumes a smooth ISM given by King (1972) and An & Baan (2012),

\[ \rho = \rho_0 \left( \frac{a_0}{z} \right)^{\beta}, \]

where \( \rho_0 \) and \( a_0 \) are the central density and characteristic length scale, respectively. The value of \( \beta \) determines the steepness of the ISM. As shown in An & Baan (2012), the linear extent of the radio lobes are a function of \( \beta \) and \( P_{\text{AGN}} \). In describing the evolution of CSOs to LSOs, An & Baan (2012) assumed a smooth ISM to derive the evolutionary tracks of CSOs. In their morphological classification and evolution of the sources they assumed that \( P_{\text{AGN}} \) is the determining factor in the evolution of CSOs. For a given morphological type there was a one-to-one correspondence between \( P_{\text{AGN}} \) and the evolutionary path.

Alternatively, a more complex set of semi-analytic models (Turner & Shabala 2015; Hardcastle 2018b) do much better at modeling the complex evolution of jet-driven radio lobes and reproducing the FR I and FR II dichotomy. In their models the jets form the familiar cocoon with jets that evolve into FR I morphologies that are disrupted or flaring close to the host galaxy. The ultimate evolution of radio lobes in their models was strongly affected by the range of pressure profiles in the cluster environment of their sample of simulated galaxies. Our simulations cover a physical scale much smaller then the models considered in Turner & Shabala (2015) and Hardcastle (2018b), but the external cluster environments of active galaxies will definitely determine the final morphology of the radio lobes.

But a clumpy ISM greatly complicates this picture. As our AGN jets grow they encounter density changes of up to six orders of magnitude before reaching the ISM–CGM boundary. With randomly generated ISMs, AGNs with the same \( P_{\text{AGN}} \) will follow widely different evolutionary paths. And, as explained above, a change in three orders of magnitude of \( P_{\text{AGN}} \) did not significantly change the morphology or total mass of the outflow (see Figure 5) when comparing jets with the same angle of inclination. This would indicate that \( P_{\text{AGN}} \), at least in the low-power regime, is a secondary factor for CSO evolution compared to the AGN angle with respect to the disk and the ISM structure within a few kiloparsec (Veilleux et al. 2020).

An & Baan (2012) explain the various evolutionary pathways taken by CSOs as they evolve to become medium symmetric objects (MSOs) and eventually large symmetric objects (LSO). One of the evolutionary scenarios shown in Figure 2 of An & Baan (2012) involves the jet interacting with the ISM causing the final radio source to be dimmer and having a morphological type consistent with an FR I source. To determine the probability of a CSO evolving into either an FR I or FR II radio galaxy we would have to consider the probability of a clear path being available to the jet. Whether or not the path is clear would depend on the jet power as higher power jets could more easily clear smaller clouds. Also it would depend on the average ISM density and the maximum cloud size in the ISM, which would determine the probability of each of the evolutionary pathways mentioned by An & Baan (2012). Considering the survey of radio sources by Mingo et al. (2019), jet–cloud or jet–ISM interactions could potentially dominate the evolution CSOs with low-power AGNs into either FR I, FR II, hybrid, or anomalous morphologies. As our simulations show, for low-power AGNs the ISM can result in a number of complex outflow morphologies with bent, split, disrupted, or suppressed jets. With the added effects of the cluster environment of the host galaxies the evolution of AGN-driven outflows is obviously complex and multifaceted.

With our small sample of simulations we obviously cannot address these issues, but hopefully our simulations can prompt more work into jet–cloud interactions, especially the case when the cloud is not fully within the jet. And also into the evolution of partially disrupted jets after leaving the disk as opposed to fully idealized jets as is standard for many jet simulations into the CGM of FR I and FR II sources (Tchekhovskoy & Bromberg 2016; Weinberger et al. 2017; Martizzi et al. 2019; Massaglia et al. 2019; Seo et al. 2021). Having a clumpy ISM should significantly affect the onset of either hydro or magnetic instabilities.

Figure 11. Same as in Figure 10 with an AGN power of \( 10^{42} \text{ erg s}^{-1} \), and from left to right inclination angles of 0°, 15°, and 75°. All simulations are shown at 600 kyrs.
7. Conclusions

Based on our simulations AGN-driven outflows have two major components (see Figure 12):

1. momentum-driven jets of high-velocity, low-density gas with laminar flow and
2. pressure-driven bubbles of multiphase, turbulent gas with a range of velocities.

Below a critical AGN power of $P_{\text{AGN}} \approx 10^{44}$ erg s$^{-1}$ the relative size and growth rate of each component depends strongly on the interaction of the AGN jet with the clumpy ISM on the kiloparsec scale. For AGNs with $P_{\text{AGN}} > 10^{44}$ erg s$^{-1}$ the ISM plays a minor role in the final morphology of the AGN-driven outflow. If a low-power jet interacts with a dense cloud in the ISM it will either slow, disrupt, or split the laminar flow of the momentum-driven jet. This interaction will increase the growth and total mass of the pressure-driven turbulent bubble. An outflow that is almost purely momentum-driven is inefficient at driving a multiphase outflow with $> 95\%$ of the gas mass being very hot ($> 10^{8}$ K). But a pressure-driven bubble will drive a multiphase outflow with roughly equal parts hot and warm gas, with a significant fraction of cold gas. Thus an AGN-driven galactic outflow driving a multiphase outflow requires some level of jet–cloud interaction.

The relative growth of the two outflow components depends on the angle of the AGN jet with respect to the galactic axis. An AGN with its jet perpendicular to the galactic disk will produce a strong momentum-driven jet and a weak pressure-
driven bubble. An AGN directed into the disk will only form pressure-driven outflows. Thus as the AGN angle goes from perpendicular to parallel to the disk the momentum-driven jet will become weaker, while the pressure-driven bubble will become stronger. This shift will not greatly affect the total mass in the outflow. But AGN angles between 30° and 60° may have a total mass outflow two to three times higher than other angles. As the AGN angle increases the composition of the outflow will go from a single hot phase to a multiphase outflow, with significantly more warm and cold gas (see Figure 5). Thus the presence of neutral or slightly ionized gas in the outflow can be useful in determining the extent of the jet–ISM interaction.

This general trend can vary due to the interaction of the jet with the clumpy ISM. For example, if a sufficiently large cloud of dense gas sits along the central axis of the jet, then Kelvin–Helmholtz instabilities will disrupt the momentum-driven jet of high-velocity gas within a few kiloparsecs. As the momentum-driven jet dissipates it will feed the growth of the turbulent bubble. In Figure 9 we see how split flows to be significant for lower-power AGNs like the ones we model. Our results indicate that a random clumpy ISM is much more effective in determining the extent of the jet–ISM interaction.

These general trends hold across three orders of magnitude ($10^{41}$–$10^{43}$ erg s$^{-1}$) of jet power. For simulations with the same AGN inclination angle but with different powers there was no significant change in the total outflow mass or outflow composition based on temperature. Thus, for these low-power AGN, the dominant variables in determining the morphology of the outflow were the orientation of the AGN with respect to the disk and the clumpy structure of the ISM, and not the AGN power. But this was not true for our simulations with $P_{\text{AGN}} > 10^{44}$ erg s$^{-1}$. Our results are in agreement with Mingo et al. (2019) who found that luminosity does not reliably predict the morphology of the radio lobes (i.e., FR type I or II) for lower-power AGNs like the ones we model. Our results indicate that the ISM within a few kiloparsecs of the AGN can significantly determine the morphology of the outflow.

With a randomly generated clumpy ISM, across the full range of possible AGN angles, only two momentum-driven jets managed to escape the disk while still maintaining relativistic laminar flow. Only these outflows could eventually form FR I radio lobes. None of our low-power simulations produced symmetric high-velocity, momentum-driven jets of equal strength and cohesion from both sides of the galactic disk. But almost all produced symmetric bubbles with a turbulent mix of ISM and jet gas. If the galactic outflows from our simulations were categorized by radio lobe morphology most would be classified as asymmetric, hybrids, or compact sources (so-called FR Os; Capetti et al. 2020). From a sample of more than 5800 radio bright sources (Mingo et al. 2019) only ~7% were FR II sources, with a similar number being hybrid sources. But the majority of sources in their survey were classified as small or compact sources. We recognize that we do not have a true stochastic sample, but this indicates an interesting avenue of investigation into how a random clumpy ISM determines the probability of different outflow morphology types, especially asymmetric or hybrid morphologies.

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