Feedback by AGN Jets and Wide-angle Winds on a Galactic Scale

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Abstract

To investigate the differences in mechanical feedback from radio-loud and radio-quiet active galactic nuclei on the host galaxy, we perform 3D AMR hydrodynamic simulations of wide-angle, radio-quiet winds with different inclinations on a single, massive, gas-rich disk galaxy at a redshift of 2–3. We compare our results to hydrodynamic simulations of the same galaxy but with a jet. The jet has an inclination of 0° (perpendicular to the galactic plane), and the winds have inclinations of 0°, 45°, and 90°. We analyze the impact on the host’s gas, star formation, and circumgalactic medium. We find that jet feedback is energy-driven and wind feedback is momentum-driven. In all the simulations, the jet or wind creates a cavity mostly devoid of dense gas in the nuclear region where star formation is then quenched, but we find strong positive feedback in all the simulations at radii greater than 3 kpc. All four simulations have similar SFRs and stellar velocities with large radial and vertical components. However, the wind at an inclination of 90° creates the highest density regions through ram pressure and generates the highest rates of star formation due to its ongoing strong interaction with the dense gas of the galactic plane. With increased wind inclination, we find greater asymmetry in gas distribution and resulting star formation. Our model generates an expanding ring of triggered star formation with typical velocities of the order of 1/3 of the circular velocity, superimposed on the older stellar population. This should result in a potentially detectable blue asymmetry in stellar absorption features at kiloparsec scales.

Key words: galaxies: active – galaxies: evolution – galaxies: jets – galaxies: star formation – Galaxy: formation

1. Introduction

Powerful active galactic nuclei (AGN) have long been predicted and observed to have tremendous impacts on the galaxies that host them, from the scale of the galactic bulge to the circumgalactic medium (CGM). A well-measured $M_{\text{BH}} \sim \sigma_*$ relationship is the first indicator of an important coevolution of the central black hole and the bulge, and several competing theories aim to explain the tight correlation (Silk & Rees 1998; Umemura 2001; Jahkke & Macciò 2011). Observations of AGN- and jet-driven outflows show that these can be massive and powerful flows and can extend up to 50 kpc away from their source (e.g., Nesvadba et al. 2006; Moe et al. 2009; Bautista et al. 2010; Liu et al. 2013b; Tombesi et al. 2014; Shih & Stockton 2015; Zakamska et al. 2016). Within a single galaxy, the impact of AGN feedback on the host’s gas and star formation will vary, depending on both the nature of the interstellar medium (ISM), how dense and clumpy the host’s gas is, as well as on the type of feedback, radio-loud or quiet, and so on (Kallfountzou et al. 2012; Wagner et al. 2013; Zinn et al. 2013). The impact on star formation in particular has remained a mystery because of the difficult nature of its observation, especially at higher redshift. Typically, negative feedback has been invoked to explain the lack of observed large, luminous galaxies predicted by ΛCDM theory (Weinmann et al. 2006). However, both recent observations and simulations have begun to paint a more complex picture.

1.1. Observations

The observational approach to establishing a well-defined relationship between AGN feedback and star formation can be difficult because the observational techniques employed to calculate star formation rates can be complicated by the presence of powerful AGN (Zakamska et al. 2016).

Many observations have led to the conclusion that AGN may quench star formation in the host. Fabian (2012) describes how both radio-loud and radio-quiet quasars drive bubbles and winds that simultaneously expel gas that might otherwise form stars from the galaxy and prevent the accretion of new gas onto the galaxy to form stars in the future. This latter process can heat intercluster gas and reduce star formation by an order of magnitude. Schwamb et al. (2016) provides evidence of negative feedback on the host through the expulsion of residual molecular gas. Morganti et al. (2015) shows that a large amount of molecular gas can be driven by relativistic jets, although not always fast enough to be expelled from the galaxy.

However, some observations indicate that AGN may not always act to quench star formation in the host. Karouzos et al. (2016) find evidence against AGN outflows as agents for negative feedback, even at small redshifts, $z < 0.1$, and low luminosities, $L < 10^{42} \text{erg s}^{-1}$. Using Gemini Multi-Object Spectograph data on six low-redshift, type 2 AGN, they find that while the outflow velocities can reach 600 km s$^{-1}$, the $<2.1$ kpc size of the outflows are too small to quench an entire galaxy. Labiano et al. (2016) examines two low-redshift radio-loud AGN with outflows in different stages of the process. Their calculated kinematics, star formation efficiency, and star formation rates indicate that AGN feedback is not necessarily responsible for the apparently low SFR in evolved AGN systems, but instead that perhaps the calculated SFRs are too low, or that the estimated molecular gas content of these galaxies is too high.
Other studies find a more complicated relationship between quasar winds and star formation in the host. Carniani et al. (2016) study two quasars with fast outflows and observe star formation, but not in the path of the wind. They conclude that the most likely possibility is one of simultaneous positive and negative feedback in the host, in which the outflows remove gas that could form stars along the direction of the wind while compressing gas around the edges of the outflow, triggering star formation. They also postulate that several cycles of feedback could be necessary to quench star formation in the host completely. Similarly, Cano-Díaz et al. (2012) observe AGN outflows quenching star formation along the path of the outflow and simultaneous star formation in the other parts of the galaxy.

Some groups attempt to establish relationships between quasar outflow velocity and star formation rates and find mixed results. Balmaverde et al. (2016) observe 224 quasars at $z < 1$ with outflows, and find that strong outflows have slightly higher SFRs than weak outflows at similar redshifts. Wyilezalek & Zakamska (2016) also observe 133 radio-quiet quasars with outflows and use the $[O\text{III}]$ emission line to determine outflow velocity. They find a positive correlation between outflow velocity and star formation rate. They also examine correlations between outflow velocity and specific star formation rate (sSFR), and observe no correlation for the overall sample but a negative correlation for those galaxies with SFRs $> 100 M_{\odot} \text{yr}^{-1}$. They postulate that these galaxies have higher gas content because of the higher SFR, and that AGN feedback has more of a negative impact with respect to star formation in gas-rich galaxies. Also important, the study shows a positive correlation between AGN luminosity and outflow velocity.

Other studies find a lack of correlation between AGN luminosity and SFR. Pitchford et al. (2016) document 513 luminous type 1 quasars with extreme star formation rates and find that for a given redshift, the SFR does not vary with AGN luminosity, black hole mass, or Eddington ratios. They find that star formation in high ionization broad absorption line quasars is not impacted by outflows and conclude that for $0 < z < 3$, star bursts in quasars typically evolve as they would without the presence of the AGN.

Still other observations indicate that radio-loud quasars are more likely to trigger star formation than their radio-quiet counterparts. Analyzing almost 20,000 quasars from the Sloan Digital Sky Survey, Kalfountzou et al. (2012) use $[O\text{II}]$ emission lines to estimate SFRs in quasars with and without jets. After finding higher SFRs in the radio-loud AGN, they conclude that the jets trigger star formation. Zinn et al. (2013) combine far-infrared and radio data on several hundred AGN from the Chandra Deep Field South to examine differences in star formation because of AGN jets. Using the far-infrared data as a tracer for star formation, they find a correlation between enhanced SFRs and radio-loud quasars, even when compared with radio-quiet quasars with similar luminosities. Their results indicate positive feedback from the mechanical energy of jets and negative feedback from the photo-dissociation and heating of molecular gas.

Some observers find evidence for AGN-triggered star formation on smaller scales, in giant molecular clouds (GMCs) and smaller clouds alike. Tremblay (2016) presents observations from ALMA, showing AGN jets can act as mechanical pumps for GMCs, blowing them away with jet-driven bubbles before gravity pulls them back. In these observations, the outer regions of the molecular clouds show star formation, possibly triggered by the expansion of the jet bubble. Cresci et al. (2015) use the Measuring AGN under MUSE Microscope (MAGNUM) survey and present evidence for positive feedback from NGC 5643, a radio-quiet AGN with outflows. They observe double sided ionization cones with high-velocity gas and star formation in clumps exposed to the resulting outflow, and they propose the compression of the clouds from the outflow is triggering the star formation. The clouds are located at 1.2 kpc. The projected velocity of the outflow is 423 km s$^{-1}$. They also find a ring of star formation at 2.3 kpc, which agrees well with theoretical studies from Gaibler et al. (2012) and Dungan et al. (2014).

1.2. Theoretical Work

Wagner et al. (2016) reviewed theoretical work on both positive and negative feedback from radio-loud and radio-quiet AGN. They conclude that the result depends on the geometry and density of the ISM, that spherical distribution of clouds and lower density of clouds cause negative feedback, while disk configurations and higher density clouds are more conducive to positive feedback. Ishibashi & Fabian (2012) also provide a theoretical framework for AGN-triggered star formation, one in which stars are formed at increasingly large distances from the center of the galaxy, an “inside-out” growth of star formation, and Zubovas & King (2016) reach a similar conclusion through analytic theory. This process is also seen in the computational studies on radio-loud AGN simulations from Gaibler et al. (2012) and Dungan et al. (2014).

To determine the feedback through pressure confinement of a jet-driven bubble, Bieri et al. (2016) increased the pressure of the ambient gas around a disk galaxy to circumvent the computational challenges posed by the velocities and resulting shocks of an actual jet. They calculate self-gravity, and find the pressure causes an increased fragmentation of dense clouds in the host galaxy and subsequent increase in star formation (positive feedback). Zubovas & King (2014) provide analytic theory of galaxy-wide outflows and find that rapid cooling in the outflow leads to a two-phase gas and subsequent star formation.

Some simulations focus on AGN feedback on smaller scales, such as shocks from jets or winds striking clouds. Zubovas et al. (2014) find that over-pressured shocks striking gas clouds cause fragmentation and star formation. Dungan et al. (2017) finds a threshold ram pressure beneath which over-pressured, high-velocity shocks with perturbations cause gas clouds to collapse and form stars.

The simulations of AGN–cloud interaction by Dungan et al. (2017) show that outflows can trigger star formation in gas clouds with significant radial velocity. This work corroborates previous simulations from Gaibler et al. (2012), Dungan et al. (2014), and Zubovas et al. (2013) and analytic theory by Silk & Mamon (2012). Interestingly, Brown et al. (2012) report that the orbits of many high-velocity stars (HVSs) appear to emanate from the center of our own galaxy, which may agree with some HVSs being caused by previous periods AGN of activity.

In this paper, we examine the role of opening angle and inclination in mechanical AGN feedback through four simulations, each on the same galaxy with different feedback parameters: a jet with a small opening angle and 0° inclination with respect to the disk, a wide-angle wind with 0° inclination,
a wide-angle wind with a 45° inclination, and a wide-angle wind with a 90° inclination. We analyze the morphology and evolution of the galaxies, feedback to the host’s gas, impact on star formation, and feedback to the CGM.

It is important to note that the employed models also comprise two different physical phenomena that we consider rather distinct, although they can and will be present concurrently at various levels for many observed objects. They are the ones also deemed responsible for the bimodality of AGN feedback as “radio mode” and “quasar mode.” On the one hand, with relativistic jets, the driving jet beams are formed through magnetic fields, are highly collimated, carry large momenta and kinetic energy before they terminate in hotspots or decollimate into plumes, but they have low-mass outflow rates. They are typically identified in observations as narrow features in radio emission (if resolutions and brightness allow). And on the other hand, slower (sub-relativistic) wide-angle AGN winds are ultimately (on the inner scales) driven by the radiation of the AGN, and hence have large opening angles, larger densities and mass outflow rate, but do not reach the extreme speeds of jet beams. While the driving processes are totally different on a theoretical level, the observational consequences may be very similar (cf. Wagner et al. 2013) and possibly even difficult to tell apart because the low-massflow jets will eventually start entraining dense, ambient gas at their contact surface and hence have some regions of higher mass flux, too. While nomenclature has grown very complex, we use the distinction “jets” versus “AGN winds/outflows” for the two phenomena, but note that also other terminology is present in the literature (e.g., “wide jets” in Sternberg et al. 2007; Soker 2016).

This paper is organized as follows. In Section 2, we review the analytic theory of bubble expansion. We describe the simulation’s numerics, setup, and AGN feedback implementation in Section 3 and the analysis in Section 4. We show the results of simulations in Section 5. We present our discussion in Section 6, and conclude in Section 7.

2. Analytical Expansion Model

For a spherically symmetric galaxy, the energy conserving analytical models of a jet or outflow driven bubbles depend only on the power of the jet or outflow (Bicknell & Begelman 1996). The equations for the bubble’s radius and resulting wind velocity are

\[ R_b = A t^{3/5} \]  
\[ v_w = (3/5) A t^{-2/5}, \]

where

\[ A = \left( \frac{125 P_{\text{jet}}}{384 \pi p_b} \right)^{1/5}. \]

If we assume that the bubble density is a function of the mass flux from a jet or outflow, Equation (1) can be rearranged and integrated, as in Wagner et al. (2012), to get the bubble density:

\[ \rho_b = 3 \left( \frac{A}{4 \pi} \right)^{3/4} M_{\text{jet}} t^{-4/5}. \]  

Now, combined with information on \( M_{\text{jet}} \) and Equation (2), the ram pressure from the bubble can be calculated. If we assume a wind with the same power as the jet from Gaibler et al. (2012), \( 5.5 \times 10^{45} \text{ erg s}^{-1} \), the mass fluxes are 0.15 and 13.32 \( M_\odot \text{ yr}^{-1} \) for the jet and wind, respectively. We show the bubble radius and velocity for several ambient densities, as well as the ram pressure calculated from the mass fluxes listed in Figure 1.

3. Simulations

Observations and simulations together capture how complicated and variable AGN feedback on star formation can be, depending on redshift, the power of the AGN, the gas content of the host, whether the AGN is radio-loud or radio-quiet, and many other factors. In this study, we seek to refine our understanding of the differences in mechanical feedback between jets and AGN winds, as well as the importance of AGN wind inclination for feedback. We examine the impact of a jet and of AGN winds at three different inclinations on the same disk galaxy’s gas distribution and velocity, star formation rates and stellar velocities, as well as potential impact on the CGM.

3.1. Numerics and Setup

We build on the four simulation runs from Gaibler et al. (2012, hereafter Paper I) that examined AGN jet activity in a massive, gas-rich disk galaxy. We construct the same thick, clumpy gaseous disk of \( 1.5 \times 10^{11} M_\odot \) with a scale radius \( r_0 = 5 \text{ kpc} \) and a scale height \( h_0 = 1.5 \text{ kpc} \), and hard cutoffs at
$r = 16 \text{kpc}$ and a height $h = 6 \text{kpc}$. The gas distribution, intended to mimic the clumpy ISM, is derived from a fractal cube computed in Fourier space and the density profile

$$\rho(x) \propto \exp\{-r/r_0\} \text{sech}^2(h/h_0)$$

for a log-normal probability distribution, with an average density of 15.6 $m_p \text{ cm}^{-3}$ and a median density of 10 $m_p \text{ cm}^{-3}$. The Fourier power spectrum has a profile of $E(k) \propto k^{-5/3}$ for large wave numbers, greater than $h_0^{-1}$, to prevent large-scale asymmetries. The ambient medium surrounding the galaxy has a density of 0.05 $m_p \text{ cm}^{-3}$. The cooling function from Sutherland and Dopita (1993) is computed for a metallicity of 0.5 Z$_\odot$ and employed with a temperature floor of $T/\mu = 10^4 K$, where $\mu$ is the mean particle mass in $m_p \text{ cm}^{-3}$. Gravity was not included for the hydro-dynamical runs due to the short timescales in the simulation compared with the disk evolution timescale and the lack of resolution on the very small scales, where collapse can occur on short timescales.

We utilize RAMSES (Teyssier 2002), a second-order Godunov-type adaptive mesh refinement code. The total computational domain is 128 kpc on a side, with maximum resolution of 62.5 pc on a side, refining wherever the cell to cell gradient exceeds 10% in pressure or density (basically all regions of interest). We employ the HLLE Riemann solver, the MonCen slope limiter, an adiabatic index of 5/3, and the “pressure fix” option, a hybrid approach that prevents negative pressures in regions with high Mach numbers.

We employ the star formation model described by Rasera & Teyssier (2006) that reproduces the Kennicutt–Schmidt relation (Kennicutt 1998). Stars are created only in regions where the number density of hydrogen is $n_H > n_s$, where $n_s$ is the star formation threshold, with a rate controlled by a fixed star formation efficiency value and the local free-fall time,

$$\dot{\rho}_s = \epsilon \rho / t_{ff},$$

where $\dot{\rho}_s$ is the star formation rate, $\epsilon$ is the star formation efficiency, and $t_{ff}$ is the local free-fall time. Star particles are formed, and their mass is removed from the gas in the host cell. Values of $\epsilon = 0.05$ and $n_s = 5 \text{ cm}^{-3}$ were chosen to yield the typical star formation rates of $\sim 150 – 200 M_\odot \text{ yr}^{-1}$ without AGN activity.

3.2. AGN Feedback

In Paper I, the bipolar jets were introduced by two adjacent cylindrical regions in the center of the disk that provide a collimated flow of gas with constant momentum input in both directions, a kinetic power of $5.5 \times 10^{45} \text{ erg s}^{-1}$, jet plasma density of $\rho_j = 5 \times 10^{-3} \text{ m}_p \text{ cm}^{-3}$, and jet velocity $v_j = 0.8 c$. In this study, we perform three new simulations of wide-angle outflows from radio-quiet AGN in the same galaxy, with three orientations with respect to the disk. These outflows have dual conical full opening angles of 90°, and inclinations to the disk plane normal of 0°, 45°, and 90°, respectively. In this paper, we label the simulations “jet-0°” for a jet with zero inclination to the disk, and “wind-0°,” “wind-45°,” and “wind-90°” for the wide-angle outflows with the three inclination values. These outflows have the same power as the aforementioned jet, and radii of 1 kpc.

### Table 1
Simulation Parameters

| Parameter | Gaibler12 | Wagner13 | This Study |
|-----------|-----------|----------|------------|
| Resolution (pc) | 62.5 | 2 | 62.5 |
| $v$ (km s$^{-1}$) | 240,000 | 30,000 | 36,203 |
| $P$ (erg s$^{-1}$) | 80 | 10 | 12.1 |
| $\theta$ (°) | $\sim 0$ | 30 | 45 |
| $M$ ($M_\odot \text{ yr}^{-1}$) | 0.15 | 0.1 | 13.32 |
| $\rho_j$ ($m_p \text{ cm}^{-3}$) | $5 \times 10^{-5}$ | 4.25 | $3.954 \times 10^{-3}$ |
| $v_{out}$ (kpc) | 0.4 | 0.01 | 1.0 |

Note. * Half opening angle.

When determining the parameters for these winds in our simulations, we start with the Eddington luminosity: $L_{\text{Edd}} = 4\pi GM_\odot m_p c / \sigma_T$. The mass of our black hole estimated from the dynamical masses of galaxies from Beifiori et al. (2012) is $\sim 1.5 \times 10^{9} M_\odot$, which leads to $L_{\text{Edd}} = 1.9 \times 10^{47} \text{ erg s}^{-1}$. With the Eddington luminosity, we can determine the Eddington accretion rate $M_{Edd} = L_{Edd} / (\epsilon c^2) = 4\pi GM_\odot m_p / (\sigma_T e c)$, in which $\epsilon$ is the radiative efficiency. Assuming $\epsilon = 10\%$, $M_{Edd} = 33.29 M_\odot \text{ yr}^{-1}$. We assume that the ratio of mass outflow rate to the Eddington accretion rate is on the same order of magnitude as the Eddington ratio, as others in the literature have (King & Pounds 2015). We employ an AGN outflow rate of 40% of the Eddington accretion rate, a reasonable value for the Eddington ratio and AGN of this luminosity (Shen et al. 2008), and we get an $M_{out} = 13.32 M_\odot \text{ yr}^{-1}$. To calculate the velocity and density of the outflow, we begin with the power of the outflow, which we set equal to that of the jet: $P_{jet} = 5.5 \times 10^{45} \text{ erg s}^{-1} = 0.5 M_{out} v^2$. For an AGN outflow with the same power and the calculated mass outflow rate, we get the densities and velocities listed in Table 1. We set the pressure of the wind inside our conical injection region to the pressure of the jet, $1.6 \times 10^{-10} \text{ dyne cm}^{-2}$, yielding nearly equivalent thermal powers of $2.4 \times 10^{43} \text{ erg s}^{-1}$ for the jet and $4.1 \times 10^{43} \text{ erg s}^{-1}$ for the winds.

4. Analysis

To quantify feedback to the gas of the galaxy, we calculate several quantities. We define the mechanical advantage as

$$MA = p_i(t) / \int_0^t p_w dt = p_i(t) / (M_{out} v),$$

where $p_i(t)$ is the instantaneous radial momentum of the host’s gas at time $t$, $p_w$ is the momentum of the wind, $M$ is the wind’s mass flux, and $v_w$ is the wind’s velocity. This expresses the efficiency of the momentum transfer to the host’s gas. To quantify the manner in which the kinetic energy from the AGN is deposited to the host, we calculate the ratio of the kinetic to internal energy of the gas,

$$E_k / E_{\text{int}} = \gamma p v^2 (\gamma - 1) / P,$$

where $\gamma$ is the adiabatic index and $P$ is the pressure. To the same end, we calculate the ratio of the kinetic energy of the
cooler gas to the total energy injected into the galaxy,
\[ E_k / E_{\text{inj}} = \rho v^2 / (P_w t), \tag{9} \]
where \( P_w \) is the power of the wind. We also estimate the velocity dispersion as a function of observation angle if calculated by an observer using absorption lines. First, we establish a line of sight coming from the center of the galaxy to the observer. We then take a line and oversample it by a factor of three more than the number of cells that would cover the line, extracting the density and velocity in the direction of the

**Figure 2.** Projections of mass-weighted gas density through the galaxy. Results from jet-i0 are in the top two panels, wind-i0 in the second two, wind-i45 in the third two, and wind-i90 in the fourth two. In the edge-on projections, the outflows initially are directed perpendicular to the disk and are gradually inclined counterclockwise. The edge-on show the perspective that best illustrates the outflow’s impact on the host. In the face-on projections, the outflow closer to the observer is initially directed out of the page, and is gradually inclined to the left, while the other side of the outflow does the opposite.
Figure 3. Face-on and edge-on density slices through the center of the galaxy. Results from jet-i0 are in the top two panels, wind-i0 in the second two, wind-i45 in the third two, and wind-i90 in the fourth two. In the edge-on slices, the outflows initially are directed perpendicular to the disk and are gradually inclined counterclockwise. The edge-on slices are not axisymmetric, and we show the perspective that better illustrates the outflow's impact on the host. In the face-on slices, the outflow closer to the observer is initially directed out of the page, and is gradually inclined to the left, while the other side of the outflow does the opposite.
observer. We then calculate the density-weighted velocity dispersion $\sigma_v$ as

$$\sigma_v^2 = \left( \frac{\sum_i \rho_i v_i^2}{\sum_i \rho_i} - \left( \frac{\sum_i \rho_i v_i}{\sum_i \rho_i} \right)^2 \right) \left( \frac{\sum_i \rho_i}{\sum_i \rho_i} \right)^2.$$  

5. Results

5.1. Morphology and Evolution

In all of the simulations, the AGN feedback creates an extended cavity in the center of the galaxy. Figure 2 shows face-on and edge-on projections of the mass-weighted density for all four simulations, and both the jet and the winds create rings of high density gas surrounding the cavity. The regions where the winds directly strike the disk develop the highest densities, especially in the simulations where the outflow continuously interacts with the disk, wind-i45 and wind-i90. The jet drills a far more diffuse hole in the center of the disk than the outflows, which may result in a more distinct ring of star formation. The outflows drive more mass off the disk, wind-i90 in particular. This outflow creates an asymmetric cavity in the center of the galaxy as the wind continues to direct strong ram pressure out along the disk through the duration of the simulation.

The winds break out of the disk between 2 and 2.25 Myr after initialization, whereas the jet breaks out after only 1.4 Myr, allowing its cocoon to begin growth and effect the host more quickly. Only after the jet breaks through the disk do the bubble evolution and feedback begin to differ from the winds. The bubbles resulting from the winds seem to grow at a similar pace, as shown in Figure 3, which displays face-on and edge-on slices of the density for all four simulations.

To better display the innermost dynamics of the feedback with the disk, we show density slices at 13.75 Myr of the central 8 kpc overlaid with velocity vectors in Figure 4. The jet generates a backflow toward the disk, while the outflow simulations all drive gas that is mostly moving radially away from the galaxy’s center. As the outflows with inclinations of 45° and 90° drive high-velocity gas into the dense disk, they generate interesting bubble features, seen as the high density semi-circles.

The bubble growth from the winds is in agreement with the analytical theory of bubble expansion in a uniform environment, as shown in Figure 1. Although the jet itself has extreme ram pressure, the bubble it generates has a ram pressure typically an order of magnitude smaller than those generated from the winds, as shown in the ram pressure slices in Figure 5 and in agreement with the analytical theory plotted in Figure 1. Figure 5 clearly shows that the high ram pressure in wind-i90 is directed straight into the high density disk for the duration of the simulation, continuously compressing this gas. This makes a substantial difference in subsequent star formation, as we discuss in Section 5.3.

Although the jet breaks out of the disk more quickly, the cocoons in all the simulations have roughly the same velocity, $\sim 1000$ km s$^{-1}$. The higher the inclination of the wind is, the more the clumpy ISM changes the direction and speed of the outflow. In wind-i90 in particular, we see the development of asymmetric high-velocity eddies and channels. In jet-i0, the velocities of the dense gas along the disk are the smallest, even when compared with wind-i0. In these two simulations, a thick ring of slow moving gas lies in the plane of the disk, with this ring being much thicker in the jet simulation.
Figure 5. Face-on and edge-on ram pressure slices through the center of the galaxy. Results from jet-i0 are in the top two panels, wind-i0 in the second two, wind-i45 in the third two, and wind-i90 in the fourth two. In the edge-on slices, the outflows are initially directed perpendicular to the disk and are gradually inclined counterclockwise. The edge-on slices are not axisymmetric, and we show the perspective that better illustrates the outflow’s impact on the host. In the face-on slices, the outflow closer to the observer is initially directed out of the page, and is gradually inclined to the left, while the other side of the outflow does the opposite.
Figure 6. Face-on and edge-on pressure slices through the center of the galaxy. Results from jet-i0 are in the top two panels, wind-i0 in the second two, wind-i45 in the third two, and wind-i90 in the fourth two. In the edge-on slices, the outflows initially are directed perpendicular to the disk and are gradually inclined counterclockwise. The edge-on slices are not axisymmetric, and we show the perspective that better illustrates the outflow’s impact on the host. In the face-on slices, the outflow closer to the observer is initially directed out of the page, and is gradually inclined to the left, while the other side of the outflow does the opposite.
However, unlike the ram pressure, the jets initially produce regions of thermal pressure higher than the maximum pressure regions in the outflow simulations. Figure 6 shows face-on and edge-on pressure slices of all four simulations. After about 10 Myr, the pressure within the jet cocoon and the outflow bubbles is about the same. In wind-i0 and wind-i45, we see regions within the extended cone of outflow that are extremely under-pressured. The outflow simulations with wind-i90, however, continue to create regions of high pressure where the wind strikes the disk directly. The temperature within the wind bubbles are roughly the same, around 10^{10} K. The jet, on the other hand, creates regions close to the jet but also close to the disk that are extremely hot, greater than 10^{11} K (but as expected for a hot plasma with highly relativistic electrons), shown in Figure 7. However, because the jet cocoon is under-dense relative to the wind cocoons, the thermal pressure is roughly the same. We also see much greater fluctuation in temperature in the cocoon of wind-i90.

Our simulations show that jets are expected to have a greater impact on the CGM than winds for two reasons. While winds create spherical bubbles, jet cocoons grow to a more conical shape, with peaks that extend much farther than the radius of the winds’ bubbles. The jet cocoon extends beyond 30 kpc, and the wind bubbles achieve radii of only 16 kpc, roughly the radius of the galaxy. Thus, the jet cocoon is more likely to strike an extra galactic cloud or satellite because of its larger size. Second, as a result of the low densities and high velocities within the jet cocoon relative to the wind bubbles, the jet cocoon has a much higher temperature. Figure 7 shows slices of the temperature and ram pressure for all four simulations 12.75 Myr after the beginning of the AGN feedback. Because of the extended structure and higher temperature, jets are more likely to impede accretion of gas onto the galaxy than winds are. However, aside from where the jet strikes its cocoon, the wind bubble’s edge is denser and has a higher ram pressure.

Figure 7. Large-scale temperature and ram pressure slices at 22.75 Myr.

Figure 8. Mass-weighted mean spherical radial velocity vs. time for various radial bins and densities. Radii are in units of kpc, and densities are in units of m_p cm^{-3}. Results from jet-i0 are in the top panel, wind-i0 in the second, wind-i45 in the third, and wind-i90 in the fourth.
5.2. Feedback to the Gas

We analyze AGN feedback to the host’s gas in two density troughs, $\rho > 0.1 \, m_p \, cm^{-3}$ and $\rho > 1 \, m_p \, cm^{-3}$, and annuli in the galaxy of 4 kpc radii. Through the various quantifications of feedback to the gas in all four simulations, we see several common trends. First, feedback to the more diffuse gas is typically stronger. This means a more efficient transfer of momentum and energy, and higher resulting velocities. Second, as a result of the bubble’s expansion through the disk in all the simulations, there is a time delay for feedback to the larger radii along the disk. Third, the feedback from a jet happens much more quickly than in the simulations with the outflows.

The radial velocity of the host’s gas in all the simulations reveals both more efficient feedback to the diffuse gas than the dense gas and the time delay to larger radii, as shown in Figure 8. For the dense gas at radii less than 8 kpc, the mass-weighted mean radial velocities reach velocities of $100 \, km \, s^{-1}$ in all four simulations. In all four simulations, the diffuse gas is accelerated to higher velocities at larger radii, typically reaching $100 \, km \, s^{-1}$ between 8 and 12 kpc and $1000 \, km \, s^{-1}$ between 12 and 16 kpc. These reflect the bubble itself, which comprises all the gas with densities greater than $0.1 \, m_p \, cm^{-3}$ at radii greater than 16 kpc, essentially outside the original galaxy. In fact, at radii greater than 16 kpc, the bow shock of the bubble can climb to densities greater than $1 \, m_p \, cm^{-3}$ and has a velocity of $1000 \, km \, s^{-1}$, which impacts the CGM.

Differences arise at larger radii. The diffuse gas at radii greater than 16 kpc is accelerated to $1000 \, km \, s^{-1}$ by the jet in less than 4 Myr because of the large velocity and the bow shock of the jet. In both jet-i0 and wind-i0, we see that the velocity of the dense gas at radii between 8 and 12 kpc ends up around $10 \, km \, s^{-1}$. However, as the inclination in the outflow simulations increases, the velocity of the same gas climbs to nearly $100 \, km \, s^{-1}$ in wind-i90, indicating that the inclination of the outflow actually has a larger impact at larger radii.

More of the kinetic energy injected from the jet than from the winds ends up as kinetic energy in the host’s gas. This is predominantly because of the effect of strong cooling in the dense gas, which reduces internal energy on short timescales. On larger scales, with lower-density gas and slower cooling, thermalization is expected to be higher. Hillel & Soker (2016)...
find that kinetic energy from the wind mixes with the gas in cluster cooling flows and ends up as internal energy. Figure 9 shows the ratio between the kinetic energy and internal energy of the host’s gas, a ratio that depends more strongly on radius than on density in all four cases. Within 16 kpc, the ratio for both the dense and diffuse gas begins and ends with similar values, typically around a value of 100. However, for the diffuse gas at radii larger than 16 kpc, more of the energy is thermal rather than kinetic, particularly in the case of the jet where high internal energy diffuse gas can be found at distances greater than 32 kpc from the galactic center. Again, we see this ratio develops more quickly in the case of a jet than the outflows, especially at the larger radii. For all gas with a density greater than 0.1 $m_p$ cm$^{-3}$ within a radius of 64 kpc, we see that this ratio approaches 1 for the jet, indicating the feedback is energy-driven. However, for the same gas in the case of all of the winds, the ratio approaches 0.1, indicating a substantially less efficient energy transfer.

The mechanical advantage, which we compute as the ratio of radial momentum to the time-integrated injected momentum, reflects that the winds are also closer to momentum-driven, while jets largely evolve in an energy-driven manner. Figure 10 shows that for all gas with a density greater than 0.1 $m_p$ cm$^{-3}$ within a radius of 64 kpc, the mechanical advantages of the winds end far closer to 1 than that of the jet. Again, we see the jet transfers momentum to the host’s gas faster than the winds do. We see the mechanical advantage decrease with increasing radius for the dense gas and vice versa for the diffuse gas, which is not generally true for the kinetic energy to injected kinetic energy ratio.

A helpful way of examining AGN impact on host morphology is to analyze the fraction of space and mass occupied by gas of certain densities. The volume filling factor in Figure 12 show similar evolutions in which the volume and mass occupied by high density gas increase for 10–12 Myr, after which they decrease, with the exception of wind-i90. In that simulation, the volume and mass fraction occupied by high density gas continue to increase through the duration of the simulation. The continuous increase is a direct result of the wind blasting directly into the disk, pushing the dense gas into more dense gas, which has important implications for star formation.

5.3. Star Formation

We find similar star formation rates for all the simulations except for wind-i90, which has an increased SFR as shown in Figure 13. Over the first 4 Myr, the SFR in the jet simulation outpaces the SFR in the wind simulations, which are all similar. During this time, the jet has not yet broken out of the galaxy, and thus all the kinetic energy goes toward very dense gas, creating regions of high density being compressed by high ram pressure and high thermal pressure, causing subsequent star formation. However, after the jet breaks out of the galaxy, the rate of increase of SFR slows. Around this time in the wind simulations, the winds break through this disk. In wind-i90, however, the wind continuously pushes straight out along the
disk and compresses the surrounding dense gas throughout the simulation. The kinetic energy in the other simulations is no longer deposited directly into the disk; rather, it goes into the bubble. For this reason, only the SFR in the wind-i90 simulation increases at the same rate throughout the simulation. After 5 Myr, the increase of the SFRs in jet-i0, wind-i0, and wind-i45 slows down, but remain remarkably similar to one another. With respect to star formation, only a significantly different inclination makes a difference, while the power of the wind or jet is the critical component.

Analogous to the similarity of the SFRs in the four cases, the locations of stars formed during the AGN feedback are also similar. Figure 14 shows the radius of star formation vs. the time of formation. As in Dugan et al. (2014), a ring of star formation begins at a radius of roughly 2 kpc at 1 Myr after feedback begins and moves outward radially in all four simulations as a consequence of the bow shock from the cocoons expanding through the disk. Also common to all four simulations is the stimulation of star formation at radii greater than 6 kpc, starting around 6 Myr after feedback begins, resulting from the compression of the disk from the expanding bubble. Not surprisingly, the pattern is extraordinarily similar in jet-i0, wind-i0, and wind-i45, with the final ring of star formation finishing between radii of 3 and 6 kpc, about 15 Myr.
after the jet or wind initialization. The main difference is again with wind-i90, where the wind pushes straight into the disk for 15 Myr. In this simulation, the ring of star formation is closer to an oval extending from 3 kpc to nearly 9 kpc.

Figure 15 shows the mass-weighted locations of star formation, along with the mean times of star formation for those locations. It shows an inside-out pattern of star formation, shown in Figure 14 and discussed previously. In this central region, star formation is quenched quickly after the jet or wind begins in all four simulations, as reflected by the mean time of star formation. The spatial distribution of star formation matches the spatial distribution of gas, including the asymmetries in wind-i45 and wind-i90. In both jet-i0 and wind-i0, the jet and wind form a very circular cavity of gas in the central region of the galaxy, with star formation tracing the edge of this cavity, forming a clear circle. In wind-i45, this region is more oval than in jet-i0 and wind-i0, and in wind-i90 it looks more oval still, tracing the direction of the wind. Additionally, in wind-i90 more than any of the other simulations, the wind seems to have caused stars to form along paths moving radially away from the galactic center, probably through accelerating clouds of gas that continue to form stars as they move. This is because a higher fraction of the wind’s kinetic energy is directed straight into the disk, compressing and accelerating clouds of gas that form stars.

Stars formed as a result of AGN feedback have positive radial velocities, particularly those formed in the dense rings of stars at radii from 3 to 6 kpc. Figure 16 is a phase plot of the radial velocity of formed stars vs. the radius of formation. The distribution of these velocities is similar between all the simulations, with the distribution of high velocities from wind-i90 extending further than in the other simulations, as reflected from the thicker ring of star formation shown in Figure 14. When analyzing this plot, it is important to remember that the star particles formed in these simulations are formed with the velocities of the gas in their birth cells, and it is reasonable to assume that the velocities of stars formed in these cells will be smaller. The analysis in Dugan et al. (2017) addresses star formation as a consequence of high-velocity AGN winds and shows that the velocities of the resulting stars will not be as high as the wind or the surrounding gas.

5.4. Observing Velocity Dispersion

Observations of AGN feedback are very difficult for a number of reasons, not the least of which is that some of the most interesting cases are at high redshift. One of the better ways to quantify the internal dynamics of a host galaxy is to measure the velocity dispersion along the line of sight. In theory, however, this approach can be problematic because of the angle of observation dependence and the asymmetric three-dimensional geometry of AGN. To quantify this dependence on geometry, we show the density-weighted velocity dispersion of absorption lines as a function of observation angle for various times for all four simulations in Figure 17. The first conclusion is the clear dependence on angle of observation, particularly at earlier times. Not surprisingly, both the jet and the wind-i0 simulations show much higher dispersions when looking down the jet or wind, a half angle of roughly 45°, rather than looking at the galaxy edge on.

In the first few Myr of feedback from both the jet and the winds, the observed velocity dispersion can vary 2.5 orders of magnitude, depending on the angle of observation. Between 1 and 2 Myr after the jet is initialized, velocity dispersions in the host can reach more than 1000 km s$^{-1}$, because the jet breaks through the disk in this window. After 5 Myr, the maximum dispersion in the galaxy with the jet can exceed the minimum dispersion by up to 1.5 orders of magnitude, whereas in the case of the winds, the disparity exceeds 2 orders of magnitude. These results indicate that the angle of observation of

Figure 13. Star formation rate. Jet and winds initialized at 10 Myr.

Figure 14. Mass-weighted phase plot of radius of formation vs. time of formation for star particles.
absorption lines is important to the measured dispersions, particularly in the early stages.

Another notable feature of this analysis is the temporal difference in the evolution of the velocity dispersion as a function of observation angle. In the galaxy that hosts the jet, the velocity dispersion reaches its final distribution far more quickly than in galaxies with conical winds. With the jet, this evolution takes just over 3 Myr after initialization, whereas with the winds it takes roughly 7 Myr. This is a common theme with respect to feedback in general. Because the jet breaks out of the disk faster than the winds, it deposits its kinetic energy and momentum to the host in a much shorter time than winds, as shown in Figures 10 and 11.

6. Discussion

Because the kinetic powers are all the same and the thermal powers are nearly the same, the jet and winds’ interaction with the disk and resulting bubbles make the difference to the feedback. We observe more thermalization in the case of the jet, leading to more energy-driven feedback. In the case of the winds, the smaller disparity in densities results in less thermalization. The feedback from the winds is momentum-driven and increasingly energy-driven with time, though not nearly to the same degree as with the jet. Energy-driven feedback depends on the thermal energy the jet deposits at the terminal shock. Conversely, the wind feedback is strongly dependent on its heavy momentum.

Our simulations exhibit many features in agreement with past observations and simulations. The locations of the star-forming regions agree well with observations of a radio-quiet quasar with dual conical outflows from Cresci et al. (2015), who observe a ring of star formation 2.3 kpc from the center of the galaxy. This result matches the rings and ovals of star formation, as shown in Figures 14 and 15, which begin at a radius around 2 kpc and then extend outward with time. They

Figure 15. Stellar mass distribution at time of formation, and mean time of formation for all star particles formed after AGN feedback is initialized at 10 Myr.

Figure 16. Mass-weighted phase plot of radial velocity vs. radius for star particles.
also observe two clouds at a radius of 1.2 kpc that are forming stars and contend that the compression from the wind has triggered the star formation. Tremblay (2016) sees similar a phenomenon but with GMCs being compressed and pushed outward by AGN while forming stars. We see the same effect in Figure 15, particularly the locations of star formation in wind-i90, which leaves a trail of star formation as clouds are accelerated radially from the nuclear region of the galaxy.

We see simultaneous positive and negative feedback in all of our simulations, as discussed in Wagner et al. (2016). The negative feedback occurs in the center of the galaxy very quickly, within a radius of 2–3 kpc and within ~3 Myr after the feedback is initialized, as shown in Figure 14. However, the same figure shows positive feedback at radii greater than 3 kpc after 1 Myr.

The asymmetry of the locations of star-forming regions, as shown in Figure 15, also agrees well with the idea of simultaneous positive and negative feedback, as described in Carniani et al. (2016). They observe two quasars with fast, ionized winds and see negative feedback within the outflow itself, but see positive feedback with star formation along the edges of the outflow. We see a similar result in our simulations, particularly in wind-i45 and wind-i90. Figure 15 shows that far fewer stars are formed within the region of the outflow, to a

| Figure 17. Density-weighted velocity dispersion as would be measured in absorption lines against a central light source. The viewing angle starts at $\phi = 0$ (observer in the disk plane), $\phi = \frac{\pi}{2}$ corresponds to an observer seeing the disk face-on and looking straight into the jet or the $i=0^\circ$ wind. $\phi = \pi$ to $\phi = 2\pi$ shows the other side of the disk, which is different only due to the stochastic perturbations in the clumpy gas distribution. The full opening angles of the winds are $\frac{\pi}{2}$. |
greater extent as the wind is pointed more directly into the disk in wind-i90. However, stars are forming around the edges of the outflow. This phenomenon is highlighted by the quenched central regions without star formation, which have different shapes as a result of the different wind inclinations.

However, our results seem to conflict with observational indications that jets are more likely to cause positive feedback than radio-quiet quasars (Kalfountzou et al. 2012). Zinn et al. (2013) even compares radio-loud and radio-quiet galaxies with similar luminosities and find that the galaxies with jets have higher SFRs. They attribute negative feedback to photo-dissociation and positive feedback to the insertion of mechanical energy. However, all four of our simulations show positive feedback, with remarkably similar SFRs in three as seen in Figure 13.

The differences in star formation may exist on smaller scales, where the differing ram pressures of the bubbles will have a strong impact on whether clouds of gas will collapse or be ablated. Dugan et al. (2017) simulates winds of varied ram pressures striking a Bonnor–Ebert sphere of 72 $M_\odot$, and finds an anti-correlation between star formation and wind ram pressure, leading up to a threshold ram pressure above which the wind ablates the cloud before star formation can occur. Although that threshold ram pressure is above the analytic theoretical expectations shown in Figure 1, we do observe that the ram pressures in bubbles generated by AGN winds are typically an order of magnitude greater than those generated by jets. That threshold ram pressure of 2e10 dynes cm$^{-2}$ is below the maximum ram pressures observed at the shocks of the jets and winds, and above many of the locations inside the bubbles generated from winds. These ram pressures would indicate that star formation will be more likely in the cocoons from jets than those from winds, despite the similarities among the SFRs in the simulations in this study.

We find an inside-out pattern of star formation in gas clouds with large radial velocities in all four simulations. These results are consistent with those from Gaibler et al. (2012), Silk & Mamon (2012), Ishibashi et al. (2013), Dugan et al. (2014, 2017), and Zubovas & King (2016). Dugan et al. (2014) evolved the stellar orbits for 1 Gyr after positive feedback from jet simulations, and found more random and less coherent stellar velocities with large positive radial and vertical velocities that effectively enlarge the galaxy. It is reasonable to expect similar patterns of stellar distributions and velocities after a Gyr in the AGN wind simulations performed in this study.

7. Conclusion

We investigate the differences in mechanical feedback from radio-loud (jet) and radio-quiet (wind) AGN, with four hydrodynamic simulations of a single, massive, gas-rich disk galaxy at a redshift of 2–3: one in which the galaxy hosts a jet at an inclination of 0° with respect to the galactic plane normal, and three of wide-angle, radio-quiet winds with inclinations of 0°, 45°, and 90°. We analyze the impact of AGN feedback on the host’s gas, star formation, and CGM. Jet feedback is energy-driven, while wind feedback is momentum-driven. Both jets and winds create a pronounced cavity, with only little dense gas left in the galactic center where star formation ceases; but we see AGN-triggered star formation at radii greater than ~2 disk heights or 3 kpc in all the simulations, indicating simultaneous positive and negative feedback in the galaxy at different locations. Cocoons from jets and winds accelerate clouds of gas where stars are forming, giving these stars larger radial and vertical velocities that may be observable as blue asymmetries in stellar velocity dispersions at different locations. The jet and winds trigger similar SFRs, but the wind at an inclination of 90° continuously compresses the host’s gas, generating high densities the most, thus causing the highest rates of star formation. More asymmetry in gas distribution and star formation location is created with larger wind inclination.

Our model generates an expanding ring of triggered star formation with typical velocity of order $1/3$ of the circular velocity, superimposed on the older stellar population. This should result in a potentially detectable blue asymmetry in stellar absorption features at kpc scales (cf. Cicone et al. 2016).
