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Relativistic jet feedback in high-redshift galaxies – I. Dynamics

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ABSTRACT

We present the results of 3D relativistic hydrodynamic simulations of interaction of active galactic nucleus jets with a dense turbulent two-phase interstellar medium, which would be typical of high-redshift galaxies. We describe the effect of the jet on the evolution of the density of the turbulent interstellar medium (ISM). The jet-driven energy bubble affects the gas to distances up to several kiloparsecs from the injection region. The shocks resulting from such interactions create a multiphase ISM and radial outflows. One of the striking result of this work is that low-power jets ($P_{\mathrm{jet}} \lesssim 10^{43}$ ergs^{-1}), although less efficient in accelerating clouds, are trapped in the ISM for a longer time and hence affect the ISM over a larger volume. Jets of higher power drill through with relative ease. Although the relativistic jets launch strong outflows, there is little net mass ejection to very large distances, supporting a galactic fountain scenario for local feedback.

Key words: hydrodynamics – methods: numerical – galaxies: evolution – galaxies: high-redshift – galaxies: ISM – galaxies: jets.

1 INTRODUCTION

Feedback from active galactic nuclei (AGNs) has long been identified as playing an important role in the evolution of galaxies (e.g. Silk & Rees 1998; Di Matteo, Springel & Hernquist 2005; Bower et al. 2006; Croton et al. 2006; Schawinski et al. 2007). It has been proposed that momentum-driven or energy-driven jets and winds powered by the central black hole significantly affect the gas content and star formation of galaxies (e.g. Silk & Rees 1998; Di Matteo et al. 2005; Murray, Quataert & Thompson 2005; Ciotti, Ostriker & Proga 2010; Dubois et al. 2013). However, only a few papers have addressed the complex nature of the interaction of such winds with a dense multiphase interstellar medium (ISM; see for example Hopkins & Elvis 2010; Gabor & Bournaud 2014; Hopkins et al. 2016). Oppenheimer et al. (2010) and Davé, Finlator & Oppenheimer (2012) have considered a galactic fountain scenario in which there is a recurrent cycle of blow out of gas and its subsequent infall. However, for galaxies of masses $\gtrsim 10^{11}$ M$_{\odot}$, Oppenheimer et al. (2010) find the need for an additional quenching mechanism, possibly due to AGN, to suppress excess accretion of gas and star formation in order to match the galaxy stellar mass function.

Our work concentrates on the role of radio galaxies in AGN feedback, specifically the role played by their relativistic jets. This is motivated by investigations of the radio/optical luminosity function, which have shown that the probability of a galaxy being a radio source increases with optical luminosity (Auriemma et al. 1977; Sadler, Jenkins & Kotanyi 1989; Ledlow & Owen 1996; Best et al. 2005; Mauch & Sadler 2007). It is the most luminous part of the optical luminosity function where discrepancies between hierarchical models of galaxy formation and observation are most apparent (e.g. Croton et al. 2006) and considerations of the radio–optical luminosity function indicate that it is in the optically luminous galaxies in which radio sources are most likely to play an important role. This reinforces the potential role of relativistic jets in AGN feedback. Nevertheless, not every optically luminous galaxy is a radio galaxy, indicating that radio galaxies are an intermittent phenomenon and that jet feedback is also necessarily intermittent.

Effects of feedback from relativistic jets have been investigated more in the context of heating the intracluster medium to prevent catastrophic cooling and accretion of gas to the cluster centre (e.g. Binney & Tabor 1995; Soker et al. 2001; Gaspari, Ruszkowski & Sharma 2012). However, relativistic jets are also expected to be one of the major drivers of feedback on galactic scale, as supported by several observational evidences of jet-ISM interaction (a few recent works being Nesvadba et al. 2007, 2008, 2011; Morganti et al. 2013, 2015; Dasyra et al. 2014, 2015; Ogle, Lanz & Appleton 2014; Tadhunter et al. 2014; Lanz et al. 2015b; Collet et al. 2016; Mahony et al. 2016). However, only a few theoretical papers (Sutherland & Bicknell 2007; Gaibler, Khochfar & Krause 2011; Wagner & Bicknell 2011b; Gaibler et al. 2012; Wagner, Bicknell & Umemura 2012) have addressed the question of how a relativistic jet interacts with a multiphase ISM of the host galaxy, and over what scales such interactions are relevant.

In this work, we extend the results presented in Wagner & Bicknell (2011a, hereafter WB11) and Wagner et al. (2012, hereafter WBU12). The simulations presented in those papers consist of gas distributed on a scale ∼1 kpc in the form of a two phase

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turbulent ISM, modelled as a fractal with a lognormal density distribution and a Kolmogorov spectrum. A number of useful parameters were derived: the average radial velocity of the clouds, the fraction of jet energy transferred to the kinetic energy of the clouds and the mechanical advantage of the interaction implied by the ratio of cloud momentum to jet momentum. The dependences of these quantities on cloud density and filling factor were examined. The simulations confirmed the results derived in Saxton et al. (2005), namely that the originally well-directed jets form an energy-driven almost spherical bubble, which processes 4π steradians of the galaxy atmosphere. Moreover, the outflow velocities derived from the simulations compare well with numerous observations of radio galaxies (WBU12). The conditions under which the thermal gas would be dispersed were also established.

In WB11 and WBU12, gas was considered to be 'dispersed' when its radial velocity exceeds the velocity dispersion of the host galaxy. However, while useful, this approach does not fully address the ultimate fate of potentially star-forming gas interacting with relativistic jets. Is it completely ejected from the atmosphere of the host – or does it simply become turbulent – impeding for a time, but not indefinitely, the formation of new stars? What happens when the jet breaks free of the dense gas surrounding the nucleus? Also, in WB11 and WBU12, the dense clouds were static without any associated velocity dispersion.

Hence, in this paper, we present the next step in this program of simulations, adding the following significant features. (1) A gravitational field typical of that of an elliptical galaxy consisting of luminous and dark matter (see Sutherland & Bicknell 2007). (2) An internal velocity dispersion for the dense thermal gas; this is used to establish an initial turbulent ISM consistent with observations of high-redshift elliptical galaxies (Förster Schreiber et al. 2009; Wisnioski et al. 2015). (3) Both phases of the ISM, consisting of hot gas at around the virial temperature and the warm gas at a temperature of about 10^4 K are distributed consistently with the gravitational field. This restricts the dense, warm gas to a region of order the core radius of the stellar distribution, thereby defining the region for jet break and the time-scale over which the jet significantly affects the distribution and kinematics of the dense gas. (4) A scale of 5 kpc for the simulations, significantly larger than the 1 kpc scale in our previous work.

In the following section (Section 2), we describe the simulation setup in detail and in Section 3 we document how the ISM is settled from its initial configuration. In Section 4, we examine the impact of a relativistic jet with power 10^{45} ergs^{-1} on the turbulent ISM. We describe the evolution of the ISM density and the multiphase nature of the ISM resulting from shocks driven by the jet. In Section 5, we examine the dependence of morphology on jet power by comparing the results of four jet simulations with jet kinetic powers ranging from 10^{43} to 10^{45} erg s^{-1}. We emphasize the efficiency of low-power jets in coupling with the ISM. In Section 6, we consider the energetics of the disturbed ISM, including a discussion of the galactic fountains revealed by our simulations and summarize the results in Section 7.

2 SIMULATION SETUP

2.1 Gravitational potential

We model the gravity of the host galaxy by prescribing a spherically symmetric isothermal potential as a function of radius r for both the dark matter and baryonic components. Let the velocity dispersions of the dark and baryonic matter be $\sigma_{\rm D}$ and $\sigma_{\rm B}$, respectively, the dark matter core radius $r_{\rm D}$, the baryonic core radius $r_{\rm B}$ and the normalized radius $r' = r/r_{\rm D}$. Let ϕ be the gravitational potential and $\psi = \phi/\sigma_{\rm D}^2$ the normalized potential. The net gravitational potential for both components is obtained by solving Poisson's equation (see Sutherland & Bicknell 2007, for a detailed derivation):

$$\frac{{\rm d}^2\psi}{{\rm d}r'^2} + \frac{2}{r}\frac{{\rm d}\psi}{{\rm d}r'} = 9\left[\exp\left(-\psi\right) + \frac{\lambda^2}{\kappa^2}\exp\left(-\kappa^2\psi\right)\right]. \quad (1)$$

The normalized potential in equation (1) is characterized by two parameters: $\lambda = r_{\rm D}/r_{\rm B}$ and $\kappa = \sigma_{\rm D}/\sigma_{\rm B}$. In our simulations, we use $\kappa = 2$ and $\lambda = 10$.

2.2 Initialization of the simulation

We initialize the simulation domain with a two phase, spherically distributed medium following the approach of Sutherland & Bicknell (2007), WB11 and WBU12. The density consists of an isothermal hot ($T \sim 10^7$ K; typical of galaxy clusters and elliptical galaxies, Allen et al. 2006; Croston et al. 2008; Diehl & Statler 2008; Maughan et al. 2012; Goulding et al. 2016) halo in hydrostatic equilibrium and a dense warm ($T \lesssim 3.4\times10^4$ K) turbulent and inhomogeneous gas. The density of the hot halo (HH) is described by

$$n_{\rm h} = n_0 \exp\left(-\frac{\mu m_{\rm a}\phi}{k_{\rm B}T}\right), \quad (2)$$

where n_0 is the central number density, $\mu = 0.6165$ is the mean molecular weight and $m_{\rm a}$ is the atomic mass unit. For this work, we choose $n_0 = 0.5\,{\rm cm}^{-3}$, similar to values of central gas densities inferred from X-ray observations of diffuse haloes around elliptical galaxies and galaxy clusters (Allen et al. 2006; Croston et al. 2008; Goulding et al. 2016). The pressure, $p = n_{\rm h}k_{\rm B}T$, is evaluated from the specified temperature and equation (2).

The density in the warm phase is distributed as a fractal with a single point lognormal density distribution and a Kolmogorov power spectrum

$$D(k) = \int 4\pi k^2 F(\boldsymbol{k})F^*(\boldsymbol{k}){\rm d}k \propto k^{-5/3}, \quad (3)$$

$F(\boldsymbol{k})$ being the Fourier transform. The fractal density distribution is created using the publicly available PYFC[1] routine (written by Alex Wagner) with mean $\mu_{\rm PDF} = 1$ and $\sigma^2_{\rm PDF} = 5$. The resultant distribution ($n_{\rm fractal}$) is then apodized to represent a spherical isotropic, turbulent distribution in the gravitational potential, as follows. Let $\sigma_{\rm t}$ be the turbulent velocity dispersion of the warm gas and $T_{\rm w}$ its temperature, with $\sigma_{\rm t}^2 \gg 3k_{\rm B}/\mu m$. Then the density distribution of warm gas is given by

$$n_{\rm w}(r, z) = n_{\rm fractal}\times n_{\rm w0}\exp\left[-\frac{\phi(r, z) - \phi(0, 0)}{\sigma_{\rm t}^2}\right], \quad (4)$$

where n_{w0} is the number density at (0, 0) (see Sutherland & Bicknell 2007, for details). For our simulations, we assume the mean central density of the warm clouds to be ~100–300cm^{-3}, which is consistent with typical densities of ISM inferred in high-Z galaxies (see e.g. Shirazi, Brinchmann & Rahmati 2014; Sanders et al. 2016). Tables 1 and 2 present the values of the parameters used in our simulations. The warm phase is initialized to be at the same pressure as the HH at a given location, so that the entire domain is in pressure equilibrium. A lower bound is placed on the density of the

[1] https://pypi.python.org/pypi/pyFC

Table 1. Parameters of the ambient gas and gravitational potential common to all simulations.

Parameters		Value
Baryonic core radius	r_B	1 kpc
Baryonic velocity dispersion	σ_B	250 km s^{-1}
Ratio of DM to Baryonic core radius	λ	2
Ratio of DM to Baryonic velocity dispersion	κ	10
Halo Temperature	T_h	10^7 K
Halo density at r=0	n_0	0.5 cm^{-3}
Turbulent velocity dispersion[a] of warm clouds	σ_t	250 km s^{-1}

Note. [a]Defines the extent of the cloud distribution in equation (4).

Table 2. Jet simulations.

Sim. label	Power (in erg s^{-1})	n_{w0} (in cm^{-3})
A	10^{45}	300
B	10^{45}	150
C	10^{44}	150
D	10^{43}	300

warm phase corresponding to a temperature of $T_{crit} = 3.4 \times 10^4$ K, beyond which the clouds are considered to be thermally unstable; gas in those cells is replaced by hot gas.

2.3 Jet parameters

Following Bicknell (1995), we express the kinetic jet power as follows. The jet parameters are the pressure p_{jet}, velocity with respect to the speed of light $\beta = v/c$, Lorentz factor $\Gamma = 1/\sqrt{1-\beta^2}$, cross-sectional area A_{jet}, adiabatic index γ_{ad} and the density parameter χ, which is the ratio of the rest mass energy to the enthalpy. The jet power is

$$P_{jet} = \frac{\gamma_{ad}}{\gamma_{ad}-1} c p_{jet} \Gamma^2 \beta A_{jet} \left(1 + \frac{\Gamma - 1}{\Gamma}\chi\right). \quad (5)$$

The parameter χ is given by

$$\chi = \left(\frac{\gamma_{ad}-1}{\gamma_{ad}}\right)\frac{\rho c^2}{p_{jet}}. \quad (6)$$

In our simulations, we inject the jet at the lower z boundary of the computation domain, $z = z_0$, assuming conical expansion between $z = 0$, the location of the black hole and $z = z_0$. The radius of the inlet region is constrained by the grid resolution such that at least 10 cells cover the jet inlet. For our simulations, we set the inlet radius to be 30 pc. The jet is injected with a half opening angle of 10° so that $z_0 \doteq 170$ pc. We initialize the jet with a given kinetic power (P_{jet}) and Lorentz factor (Γ). We assume the jet to be in pressure equilibrium with the gas at the inlet, thus constraining the parameter χ from equation (5); this in turn defines the jet density. For the simulations presented here, $\chi \gtrsim 5$. We assume an ideal equation of state with $\gamma_{ad} = 5/3$, which is a reasonable approximation for a relativistic gas in with $\chi \gg 1$ (Synge 1957; Mignone & McKinney 2007). Also, a non-relativistic ideal equation of state is a better descriptor of the thermal gas inside the simulation domain and it is mainly the effect on the thermal gas in which we are interested.

Adoption of such a value of χ raises questions about jet composition, which is not very well constrained for extragalactic jets (see the discussion in Worrall 2009). An electron–positron jet would have $\chi \sim 1$ and this value would be obtained if the jet were overpressured with respect to the ISM by a factor of 5. On the other hand, if the jet is in pressure equilibrium with the ISM, then it may entrain some thermal material as it travels to ∼170 pc from the nucleus, which is the starting point of our simulation.

As Worrall (2009) has noted, the dominant contribution in radio power, comes from sources around the FRI/FRII break, corresponding to the peak of the curve $P\Phi(P)$, where P is the radio power and $\Phi(P)$ is the number density of sources per unit log P. The relationship between radio power and jet power is not straightforward (see e.g. Godfrey & Shabala 2016). Nevertheless, Rawlings & Saunders (1991) identified 10^{43} erg s^{-1} as the low end of the FRII population; Bicknell (1995) found the FRI/FRII break jet power to be $\sim 2 \times 10^{42}$ erg s^{-1}. Hence, in this paper, we concentrate on jet powers ranging from 10^{43} to 10^{45} erg s^{-1}, whilst noting that investigations of jets of both lower and higher powers are certainly of interest.

2.4 PLUTO setup

We perform 3D relativistic hydrodynamic simulations using the PLUTO code's Relativistic Hydrodynamic (RHD) module (Mignone et al. 2007). We use a Cartesian geometry with a uniform grid of resolution 6 pc for the central 3 kpc, followed by a geometrically stretched grid with stretching ratio of ∼1.0128, extending up to ±2.4 kpc along the x–y directions and ∼5.2 kpc in the z direction. The total number of grid points along the x–y–z directions are 668 × 668 × 640. We use the piecewise parabolic method (Colella & Woodward 1984; Martí & Müller 1996) for the reconstruction step of the Godunov scheme, which is well suited for non-uniform grids. The time evolution is carried out using third-order dimensionally unsplit Runge–Kutta method. The HLLC Riemann solver (Toro 2008) is used for solving the hydrodynamic equations.

The non-equilibrium cooling function was evaluated from the Mappings 5.1 code (Sutherland et al., in preparation). This code is the latest version of the MAPPINGS 4.0 code described in Nicholls et al. (2013) and Dopita et al. (2013), and includes numerous upgrades to both the input atomic physics (CHIANTI v8, Del Zanna et al. 2015) and new methods of solution. MAPPINGS V includes up to 30 elements from H to Zn, of which about 10–15 provide most of the cooling. For most temperatures, oxygen and iron dominate the cooling except in some temperature regimes (very hot and 10^4 K), where collisional cooling of hydrogen and helium are key. In these models, we have adopted solar abundances from Asplund et al. (2009) as representative of metallicities of larger host galaxies.

The cooling function is constructed by having the plasma initially fully ionized at an extremely high temperature, 10^9 K, where the thermal cooling is primarily free–free emission, and the ions are fully stripped. This high temperature is outside the range expected in the simulations, and in a regime where cooling is unimportant. Without more detailed microphysics, such as a fully relativistic treatment of free–free emission for example, the MAPPINGS cooling functions above $\sim 10^{8.5}$ K or so are not intended for detailed model fitting, but serve as a smooth upper boundary to the cooling which improves the numerical properties of the cooling treatment. For gas below $T < 10^4$ K cooling was deactivated.

The plasma in the MAPPINGS model is allowed to cool in a time-dependent isobaric way, similar to a post-shock flow (Sutherland &