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| 書籍名 | Relativistic jet feedback in high-redshift galaxies: I. Dynamics |
| 出版誌名 | Monthly notices of the Royal Astronomical Society |
| 巻 | 461 |
| 号 | 1 |
| 頁 | 967-983 |
| 年 | 2016-09 |
| 許可状況 | 本論文は、オックスフォード大学出版社の許諾の下、Royal Astronomical Societyの権利に基づいて公開されています。 |
| URL | http://hdl.handle.net/2241/00144241 |
| DOI | 10.1093/mnras/stw1368 |

doi: 10.1093/mnras/stw1368
Relativistic jet feedback in high-redshift galaxies – I. Dynamics

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Accepted 2016 June 3. Received 2016 June 3; in original form 2016 April 14

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 ($P_{\text{jet}} \lesssim 10^{43} \text{ergs}^{-1}$), 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 $\gtrsim 10^{11} \text{M}_\odot$, 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 $\sim 1 \text{kpc}$ in the form of a two phase...
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 4πτ 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, with 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 ≲ 3.4 × 104 K) turbulent and inhomogeneous gas. The density of the hot halo (HH) is described by

\[ n_h = n_0 \exp \left( -\frac{\mu m_w \phi}{k_B T} \right), \]

where \( n_0 \) is the central number density, \( \mu = 0.6165 \) is the mean molecular weight and \( m_w \) is the atomic mass unit. For this work, we choose \( n_0 = 0.5 \text{ cm}^{-3} \), 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, \( p = n_h k_B T \), 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

\[ D(k) = \int 4\pi k^2 F(k) F^*(k) dk \propto k^{-5/3}, \]

\( F(k) \) being the Fourier transform. The fractal density distribution is created using the publicly available pyFC\(^1\) routine (written by Alex Wagner) with mean \( \mu_{\text{pyFC}} = 1 \) and \( \sigma^2_{\text{pyFC}} = 5 \). The resultant distribution (\( n_{\text{fractal}} \)) is then apodized to represent a spherical isotropic, turbulent distribution in the gravitational potential, as follows. Let \( \sigma_t \) be the turbulent velocity dispersion of the warm gas and \( T_w \), its temperature, with \( \sigma_t^2 \gg 3k_B/\mu m_w \). Then the density distribution of warm gas is given by

\[ n_w(r, z) = n_{\text{fractal}} \times n_{w0} \exp \left[ -\frac{\phi(r, z) - \phi(0, 0)}{\sigma_t^2} \right], \]

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 \( \sim 100–300 \text{ cm}^{-3} \), 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

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

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Adoption of such a value of $\chi$ 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 $\sim 170$ 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 $\sim 1.0128$, extending up to $\pm 2.4$ kpc along the $x$–$y$ directions and $\sim 5.2$ kpc in the $z$ direction. The total number of grid points along the $x$–$y$–$z$ directions are 668 $\times$ 668 $\times$ 640. We use the piecewise parabolic method (Colella & Woodward 1984; Marti & Miiller 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$^7$ 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 $\sim 10^{5.5}$ 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 $T < 10^5$ 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 &...
Density (\(\log [n(\text{cm}^{-3})]\)) in the \(x-z\) plane for settling turbulent ISM at two different times. The ISM develops a filamentary structure, typical of a turbulent medium.

Dopita 1993; Allen et al. 2008). Cooling down to \(10^6\) K proceeds with equilibrium ionization and cooling, until the cooling becomes rapid compared to the recombination time-scales and the ionization lags behind, being more ionized at a given temperature than in equilibrium. Below \(10^6\) K, the cooling rates increase to a maximum around \(\sim 10^5\) K, before falling rapidly below \(10^4\) K. At each point, the full ionization state including electron densities and atomic level populations, are solved, allowing the cooling and a simple equation of state to be inferred from the self-consistently changing mean molecular weight \(\mu(T)\). The gas is assumed to be atomic, and to have an ideal adiabatic index of \(5/3\). The temperature-dependent cooling function and mean molecular weight thus obtained were tabulated as a function of the ratio of pressure and density \((p/\rho)\), which are PLUTO primitive variables. The cooling losses \((\rho/\mu(T)^2\Lambda(T))\) for each cell in the PLUTO domain were applied by interpolating the cooling function and mean molecular weight from the tabulated list.

3 SETTLING OF ISM

(i) Filamentary ISM: we initialize the velocity in the warm cloudy medium with a turbulent velocity distribution, modelled as a random Gaussian variate for the three velocity components with a Kolmogorov spectrum in Fourier space. We set the velocity dispersion of the clouds higher than that of the baryonic dispersion of the galaxy and let the clouds settle in the potential. The fractal clouds disperse and shear due to the turbulent motions and cloud–cloud collisions. The clouds eventually condense into filaments, typical of a turbulent medium (e.g. Federrath & Banerjee 2015; Federrath 2016) as shown in Fig. 1. After \(\sim 1\) Myr, the turbulent distribution settles into a two phase medium (see Fig. 1) characterized by a distribution of warm filaments extending up to \(\sim 2\) kpc and an HH extending to larger radii.

(ii) Density PDF and two phase ISM: in Fig. 2, we show the volume-weighted probability distribution function (PDF)

\(^2\) of the density at different times of the simulation. Initially \((t = 0)\), the density PDF shows two distinct distributions: (a) the warm fractal clouds with high density, (b) a low-density HH. As the ISM evolves under the influence of the turbulent velocity field and gravity, the density PDF changes due to shearing of the clouds. The density PDF converges well after 1 Myr into a two component PDF corresponding to a two phase medium. The turbulent motions result in stripping of the dense clouds, lowering the mean of the high-density component of the PDF. The dispersed cloud mass forms a denser halo of gas near the central region.

Density structures formed as a result of hierarchical turbulent processes are expected to exhibit a lognormal probability distribution (e.g. Vazquez-Semadeni 1994; Padoan, Jones & Nordlund 1997; Klessen 2000). However, recent simulations have shown significant deviation from a lognormal behaviour in the tail of the distribution (Federrath et al. 2010; Konstandin et al. 2012; Federrath & Klessen 2013; Federrath & Banerjee 2015). Hopkins (2013) has shown that a lognormal-like distribution modified by the influence of intermittency from turbulent shocks is a better descriptor of the PDF in such cases (see Appendix A for a brief summary of the analytical expressions). For our simulations, we find the Hopkins

\(^2\) The volume-weighted PDF of variable is constructed by evaluating the histogram and counting the fractional volume of a simulation cell as the weights for a histogram bin.
function to provide a good fit to the high-density component of the PDFs. For example, the black-dotted line in Fig. 2 shows the Hopkins function with parameters $\bar{\rho} = 15$ cm$^{-3}$, $\sigma_\rho = 39.78$ cm$^{-3}$, $\eta = 0.08$, which provides a good fit to the high-density portion of the PDF at $t \sim 2.7$ Myr. For the rest of the paper, we have used the Hopkins function to fit the high-density end of the density PDF and compare the statistics of the ISM under different conditions.

(iii) Volume filling factor: in Fig. 3, we show the change in the volume filling factor, defined as the total volume occupied by the gas beyond a threshold density, plotted as a function of density. At $t = 0$, the volume filling factor for $n > 10$ is $\lesssim 0.045$. As the clouds shear and settle into filaments, the filling factor is lowered for the high-density cores as the warm gas is dispersed.

(iv) Decay of turbulence: as the clouds settle, the velocity dispersion decreases as a power law with time. A power-law decay of velocity dispersion (with exponent $-1.2$–$-2$) is typical of hydrodynamic supersonic turbulence (Mac Low et al. 1998; Stone, Ostriker & Gammie 1999). The rate of decay does not depend on the initial velocity dispersion. For example, as shown in Fig. 4, the rate of decay for $\sigma_{\text{ini}} = 500$ and $\sigma_{\text{ini}} = 300$ for the same $n_{\text{ini}} = 300$ is similar (with the power-law exponent $\alpha \sim -0.58$). However, as a result of the presence of atomic cooling and external gravity, the rate of settling depends on the mean cloud density and the potential of the galaxy. The settling rate is slower for lower mean cloud density and a gravitational potential with higher stellar dispersion.

4 JET SIMULATIONS

4.1 Evolution of the density of the ISM

We first let the ISM settle into a turbulent filamentary structure with a velocity dispersion $\sim 100$–$150$ km s$^{-1}$, which is typical of high-redshift galaxies (Forster Schreiber et al. 2009; Wisnioski et al. 2015). We then inject the relativistic jet whose parameters are described in Section 2.3. We list the simulations performed with jets interacting with the turbulent ISM in Table 2. In Figs 5 and 6, we present the evolution of the density, radial velocity, pressure and temperature of the ISM for simulation A. The jet is initially impeded by the dense filaments (Fig. 5) and passes through a flood-channel phase as described in previous works (Sutherland & Bicknell 2007; WB11; WBU12), seeking the paths of least resistance as it drives an energy bubble through the ISM.

The jet shears the dense filaments as it clears its path. The effect of shearing of the dense cores is well demonstrated through the evolution of the density PDF shown in Fig. 7. The high-density tail of the PDF is significantly reduced as the jet-driven bubble shears the clouds. There is a subsequent enhancement of the PDF at $n \sim 10$–$100$ cm$^{-3}$, which occurs both as a result of compression of low-density gas from the forward shock and also of fragmentation of the dense filaments. Coefficients of fits (following equation A7) at the high-density end of the PDF are listed in Table 3. The density PDF converges after the jet breaks out (jet head $\gtrsim 3$ kpc) and decouples from the ISM, proceeding along the cleared path.

The duration of the flood-channel phase of the jet evolution depends upon the mean density and filling factor of the ISM, as previously discussed in WBU12. Clouds with denser cores are less ablated and more efficiently impede the progress of the jet. In Fig. 8, we present the density for simulation B (Table 2), where a jet of power $10^{45}$ ergs$^{-1}$ passes through a medium with lower mean density ($n_{\text{ini}} = 150$ cm$^{-3}$) compared to that of simulation A. We note that the jet breaks out of the warm dense gas much faster, in comparison to simulation A.

4.2 Evolution of the energy bubble

The confined jet creates an expanding energy bubble. A fast moving forward shock first sweeps through the filaments heating the gas to $\sim 10^5$ K (see Fig. 6). The forward shock is followed by a slower moving region of nearly homogeneous high pressure, defining the energy bubble (see Fig. 6). The energy bubble shears the dense filaments as it expands into the ISM, accelerating the dense clouds to radial velocities in excess of $\sim 300$ km s$^{-1}$ (as shown in Fig. 9), as also reported earlier in WBU12. Some of the clouds are dragged

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**Table 3. Coefficients of the fit to the density PDF in Fig. 7 following equation (A7).**

| $\rho_{\text{peak}}$ (in kpc) | $\bar{\rho}$ (in cm$^{-3}$)$^a$ | $\sigma_\rho$ (in cm$^{-3}$)$^b$ | $\eta$ | $\bar{\rho}_{>10}$ (in cm$^{-3}$)$^c$ |
|-----------------------------|---------------------|---------------------|------|---------------------|
| 0                           | 21.38               | 52.68               | 0.14 | 50                  |
| 1                           | 18.42               | 44.17               | 0.14 | 43.96               |
| 3                           | 15.73               | 27.9                | 0.12 | 33.56               |
| 5                           | 13.21               | 20.52               | 0.17 | 29.5                |

Notes: $^a$Mean density for the PDF.

$^b$Standard deviation of variable $\rho$, which is related to the standard deviation in $s = \ln \rho$ as in equation (A8).

$^c$Volume-weighted mean of density for $n > 10$ cm$^{-3}$. This gives a measure of the mean density of the high-density filaments.
Figure 5. Left: density (in cm$^{-3}$) in the $x$-$z$ plane at different times for simulation A (Table 2). Right: radial velocity (in units of 100 km s$^{-1}$) at the same time as left. Dense clouds are pushed radially outwards to several hundred km s$^{-1}$. Low-density ablated cloud mass is accelerated to speeds exceeding $\gtrsim 1000$ km s$^{-1}$. 
Figure 6. Left: temperature $[\log (T), \text{with } T \text{ in Kelvin}]$ in the $x$–$z$ plane at times same as in Fig. 5. Right: pressure $[\log (p/p_0), p_0 = 9.2 \times 10^{-4} \text{ dynes cm}^{-2}]$. The second panel on the left shows the location of the forward shock ($T \sim 10^5 \text{ K}$) preceded by the energy bubble ($T > 10^6$). Corresponding features can be identified in the plot of the pressure on the right. High-pressure knots from recollimation shocks can be clearly identified in the third and fourth panels on the right.
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Figure 7. The evolution of the density PDF as the jet evolves with time and breaks out of the dense central region after a height of $z \sim 3$ kpc. The density PDF converges after jet break out as the jet decouples from the ISM.

Figure 9. The mass-weighted mean radial velocity ($\int \rho v d^3x / \int \rho d^3x$) of the warm clouds driven out by the expanding jet-driven bubble.

Figure 8. Density (log $[n(\text{cm}^{-3})]$) in the $x-z$ plane for simulation B.

Figure 10. Evolution of the mean pressure inside the energy bubble as a function of time. The red solid lines represent power-law fits to the curves to sections representing before and after the jet break out. The slopes obtained from the fits are noted above the curves.

4.3 Evolution of the phase space

(i) Multiphase ISM: phase-space diagrams are a useful way to understand the nature of the gas, where different phases of the ISM driven by different
The coupling of the jet with the ISM depends significantly on the jet power. Jets with higher power, although more efficient in driving powerful outflows, drill through the ISM more rapidly causing less shredding of the cloud cores situated a kiloparsec away from the jet axis. Low-power jets, on the other hand, remain trapped in the ISM for a longer time (see Fig. 15), interacting with the ISM over a much larger volume. In Fig. 16, where we compare the density for jets of different power at a time when the jet head is approximately at the same height for left-hand and right-hand panels. Jets with a power $\sim 10^{35}$ ergs$^{-1}$ evacuate a central cavity of radius $\sim 0.5$ kpc, whereas simulation C with $P_{\text{jet}} = 10^{33}$ ergs$^{-1}$ a larger cavity ($r \sim 1$ kpc) is evacuated. The situation is more marked for simulation D with $P_{\text{jet}} = 10^{35}$ ergs$^{-1}$, where a larger central cavity is evacuated leaving only a few of the densest cores. The density PDFs of the simulation snapshots in Fig. 16 are presented in Fig. 17. The coefficients of the fits to the high density portion of the density PDF following equation (A7) is presented in Table 5. For simulations with low-power jets, the mean density and dispersion of the density PDF is less than half of their counterparts with $P_{\text{jet}} = 10^{35}$ ergs$^{-1}$. This indicates more shredding of the dense cores by the trapped energy bubble.

The evolution of the phase space is also significantly different for simulation D, as shown in Fig. 18. Unlike the high-power jets, the phase space of the ISM cannot be distinctly divided into a high-pressure energy bubble and gas shocked by the forward shock. The energy bubble is depicted by a horizontal branch in the left-hand panel of Fig. 18. Comparing with the left-hand panel of Fig. 12 depicting the initial condition of the ISM before the jet injection, we find the bubble for Sim. D to be very weakly overpressured. Most of the gas swept up by the bubble is shocked to $10^5$ K as mentioned above without any appreciable increase in radial velocity. The clouds are primarily accelerated by the high-pressure energy bubble to speeds of $\gtrsim 500$ km s$^{-1}$. In the right-hand panels, we see a tail of very high velocity $\gtrsim 1000$ km s$^{-1}$ with less mass weight. This corresponds to the low-density cloud ablated material swept up by the energy bubble to high radial speeds, as shown in Fig. 5.
Figure 12. Top: mass-weighted 2D PDF of pressure versus density at times corresponding to plots in Fig. 5. $p_0 = 9.2 \times 10^{-4}$ dynes cm$^{-2}$ is the scale pressure of the simulation. The colour bar denotes the probability. The red dotted line for an isothermal gas is presented to highlight that dense gas closely approximates an isothermal distribution at $t = 0$. The white dashed line represents fits to the mean pressure for the phase corresponding to the energy bubble. The pressure is only weakly related to the density for this phase. Bottom: mass-weighted 2D PDF of temperature versus density. The different ISM phases are labelled as described in Table 4.

Table 4. Summary of different ISM phases.

| Phase | Description | Characteristics |
|-------|-------------|-----------------|
| HH    | Hot Halo    | The ambient low-density hot halo. Temperature: $T \sim 10^7$ K. |
| WC    | Warm clouds | Turbulent warm ($T \sim 10^4$ K) dense filaments describing the initial ISM. |
| FS    | Forward shock | Shocked ISM behind the initial forward shock. Temperature: $T \sim 10^5$ K. Very little acceleration from initial turbulent velocity. |
| EB    | Energy bubble | High-pressure energy bubble expanding nearly adiabatically for $P_{jet} \gtrsim 10^{44}$ ergs$^{-1}$. Temperature: $T \sim 10^6$–$10^7$ K. Accelerates clouds to outward radial velocities $\gtrsim 500$ kms$^{-1}$. |
| RSG   | Remnant shocked gas | ISM shocked by the forward shock which remains after jet has decoupled. These represent cooling dense cores of the clouds. |

6 ENERGETICS OF THE JET-DISTURBED ISM

6.1 Kinetic energy imparted to the ISM

For any jet power, the jet couples strongly with the ISM initially as it drills through the dense medium. Fig. 19 shows the evolution of the kinetic energy of the dense ISM ($\rho > 1$ cm$^{-3}$) for different simulations. The kinetic energy rises with time and then decreases after the jet breaks out and decouples from the ISM. For a jet of power $\sim 10^{45}$ ergs$^{-1}$, the kinetic energy of the ISM increases by a factor of 6 or more, whereas for $P_{jet} \sim 10^{44}$ ergs$^{-1}$ the kinetic energy increases by a factor of 3. The efficiency of jet feedback is better illustrated by plotting the ratio of the kinetic energy of the medium to the total integrated energy input of the jet as a function of time (lower panel in Fig. 19). We see that $\sim 25$–$30$ per cent of the jet energy is injected into the ISM, for jets of power $\gtrsim 10^{44}$ ergs$^{-1}$. This is similar to the previous results of (O’Neill et al. (2005), Gaibler et al. (2009), WBU12 and Hardcastle & Krause (2013), where initially the jet is shown to impart $\sim 20$–$30$ per cent of its energy as kinetic energy to the ISM, while the rest is deposited as internal energy, a fraction of which will be radiated away. More detailed analysis of the energy budget will be presented in a future work.
Figure 13. Mass-weighted 2D PDF of \( \log(M) \) versus \( \log(\rho) \) at times corresponding to plots in Fig. 5. The dashed line represents fits to the mean pressure.

Figure 14. Mass-weighted 2D PDF of temperature versus radial velocity (top) and density versus radial velocity (bottom) at times corresponding to plots in Fig. 5. After the jet injection, the warm dense medium is shocked to \( \sim 10^5 \) K by the forward shock without an appreciable increase in velocity. Dense gas is accelerated to radial velocities \( \gtrsim 500 \text{ km s}^{-1} \) by the hot pressure bubble.

The evolution of the kinetic energy is however very different for a low-power jet as in Sim. D with \( P_{\text{jet}} = 10^{43} \) ergs \(^{-1} \), due to the weakly overpressured nature of the bubble. Although the jet strongly interacts with the ISM in its immediate surroundings, the total kinetic energy of the ISM decreases with time. This is because the jet evolves very slowly and at the initial stages the outer layers of the turbulent ISM are not affected. Even at later stages, since the weakly overpressured bubble evolves very slowly, the bulk kinetic energy of the gas decreases as a result of atomic cooling. Thus, simply computing the ratio of the total kinetic energy of the ISM to the energy injected by the jet as an indicator of the effect of feedback of the jet on the ISM is misleading in this case. The effect of the jet on the density PDF is a better probe of jet-ISM coupling for such cases.

6.2 Galactic fountains and the effect on star formation

Although the high-power jets (\( P_{\text{jet}} \gtrsim 10^{45} \) ergs \(^{-1} \)) launch very fast outflows with speeds \( \gtrsim 500 \) km s\(^{-1} \), the fraction of total mass ejected from the influence of the galaxy’s potential is small. In Fig. 20, we show the maximum radial distance the accelerated gas may reach by assuming a ballistic trajectory for the gas and solving \( \phi(r_{\text{max}}) - \phi(r_0) = v_0^2/2 \), for the maximum radius \( r_{\text{max}} \), where \( r_0 \) and \( v_0 \) are the initial radius and radial velocity, respectively. In this way, we estimate the fractional mass of the ISM that will reach a given distance. The escape fraction is computed after the jet break out when the jet has decoupled from the ISM and the kinetic energy of the ISM saturates as shown in Fig. 19. We see that only a small fraction of the gas (\( \lesssim 5 \) per cent) goes beyond 10 kpc. Simulation B
with lower initial mean density has a larger fraction of mass ejected, as the less dense gas is easier to accelerate. For $P_{\text{jet}} = 10^{43}$ ergs$^{-1}$, all of the gas is retained within $\sim 5$ kpc. This indicates that although powerful jets can launch fast outflows, the fractional mass-loss is very small and is slightly higher for an ISM with lower mean density.

The implication of this result is that the gas is not completely dispersed even though it is accelerated to a radial speed exceeding the velocity dispersion. Instead it forms a galactic fountain in which the gas eventually falls back into the central regions of the galaxy. There may be a temporary inhibition of star formation as a result of the driving of gas out to a few kpc and the production of turbulence. Thus, turbulent kinetic energy injected by the jet is probably a more important regulator of star formation activity than mass-loss by outflows, as also reported recently in the observational papers by Lanz et al. (2015a) and Alatalo et al. (2015). We have calculated the mean velocity dispersion in our simulations by computing the variance of the three velocity components from adjacent cubes of dimensions $5 \times 5 \times 5$ cells in the simulation domain. The jet-driven energy bubble significantly increases the turbulent velocity dispersion of the swept-up gas, as shown in Fig. 21. The mass in the swept-up shell is seen to have significantly high-velocity dispersion indicating the existence of strong turbulent motions, which can significantly affect star formation (Krumholz & McKee 2005; Federrath & Klessen 2012). Detailed quantitative analysis of the effect of jets on the star formation rate in the host galaxy will be addressed in a future work.

7 SUMMARY AND DISCUSSION
Let us now summarize the main results from this work as follows.

(i) Filamentary nature of settling ISM: the simulations of the settling, turbulent ISM result in elongated filaments of dense gas, rather than spheroidal clouds. The filaments are caused by shearing of dense clouds and turbulent mixing; this feature is also seen in simulations of driven turbulence (see Federrath & Klessen 2012; Federrath & Banerjee 2015, and references therein). Recent observations with high spatial resolution of high-redshift galaxies also report a filamentary nature of the
Figure 16. Density (in cm$^{-3}$) at the x-z plane for different simulations. Upper panel: jets of power $10^{45}$ erg s$^{-1}$ (left, Sim. A) and $10^{43}$ erg s$^{-1}$ (right, Sim. D) passing through the same initial ISM derived from a relaxed turbulent fractal with $n_{w0} = 300$ cm$^{-3}$ (see Sections 2.2 and 3 for details). Lower panels: jets of power $10^{45}$ erg s$^{-1}$ (left, Sim. B) and $10^{44}$ erg s$^{-1}$ (right, Sim. C), for an ISM initialized with $n_{w0} \sim 150$ cm$^{-3}$.

Figure 17. The density PDF of the ISM of simulations corresponding to Fig. 16. The PDF of the ISM before the injection of the jet is represented in black. The jets of lower power are more effective in destroying the high-density cloud cores.

Table 5. Coefficients of the fit to the density PDF in Fig. 16.

| Sim. A | Sim. D | Sim. B | Sim. C |
|--------|--------|--------|--------|
| No. Parameter | $t = 0$ | $P_{45}$ | $P_{45}/100$ | $t = 0$ | $P_{45}$ | $P_{45}/10$ |
| 1 | $\rho$ in cm$^{-3}$ | 21.38 | 16.51 | 7 |
| 2 | $\sigma_{\rho}$ in cm$^{-3}$ | 52.68 | 31.27 | 9.32 |
| 3 | $\eta$ | 0.14 | 0.11 | 0.37 |
| 4 | $\rho_{>}$ in cm$^{-3}$ | 50 | 35.54 | 20.19 |
| No. Parameter | $t = 0$ | $P_{45}$ | $P_{45}/10$ |
| 1 | $\rho$ in cm$^{-3}$ | 12.32 | 9.17 | 3.98 |
| 2 | $\sigma_{\rho}$ in cm$^{-3}$ | 24.74 | 15.88 | 7.52 |
| 3 | $\eta$ | 0.19 | 0.15 | 0.28 |
| 4 | $\rho_{>}$ in cm$^{-3}$ | 34.2 | 26.63 | 21 |

Note. $P_{45} = P_{jet} = 10^{45}$ ergs$^{-1}$

(ii) Evolution of the energy bubble and multiphase ISM: the jet launches a high-pressure energy bubble, which sweeps through the ISM. The bubble is preceded by a forward shock, which heats the filaments to temperatures $\sim 10^5$ K but does not

extended halo of gas (Swinbank et al. 2015a,b; Wisotzki et al. 2016). After $\sim 2$ Myr, corresponding approximately to half the dynamical time $\sim r_{BL}/\sigma_{BL}$, the filaments settle to form a turbulent central region of warm gas ($T \sim 10^5$ K) extending to about $\sim 2$ kpc and an HH ($T \sim 10^7$ K). Fig. 3 shows the volume filling factor of the ISM, with the dense gas ($n > 10$ cm$^{-3}$) having a filling factor $< 0.1$. 

ii) Evolution of the energy bubble and multiphase ISM: the jet launches a high-pressure energy bubble, which sweeps through the ISM. The bubble is preceded by a forward shock, which heats the filaments to temperatures $\sim 10^5$ K but does not
The evolution of the ISM is significantly different from that of the high-power jets, as inferred by comparing similar plots presented in Figs 12–14. A significant amount of the gas remains in the mildly hot phase ($\sim 10^5$ K) from the forward shock. The temperature–velocity plot shows very little outward radial acceleration of the gas.

The temperature–velocity plot shows very little outward radial acceleration of the gas.

The evolution of the kinetic energy of the dense ISM ($\rho > 1$ cm$^{-3}$) with time. The top panel shows the fractional increase of the kinetic energy of the ISM from its initial value. The lower panel plots the kinetic energy at a given time normalized to the total energy injected by jet till that time, indicating the efficiency of coupling of the jet.

The kinetic energy vs time plot shows the energy injection and its distribution over time for different simulations.

The escape fraction vs radius plot shows the fraction of gas escaping the ISM at different radii for different simulations.

Radially accelerated to velocities of $\sim 500$ kms$^{-1}$. Such velocities are in agreement with observations of jet-driven outflows (see for example WBU12; Collet et al. 2016, and references therein).

(iii) Feedback from low-power jets:

a significant result from this work is the effect of low-power jets on the ISM of the host galaxy. High-power jets, although more effective in launching faster outflows, are less destructive of the ISM since they efficiently drill through the ISM. Low-power jets lack sufficient momentum to readily pierce the ISM and remain trapped for a longer time. This results in a more lateral spreading of the trapped energy bubble which causes enhanced shearing of the ISM filaments (as shown in Figs 16 and 17). Such persistent coupling of a trapped jet with the ambient ISM will result in constant stirring of the turbulent ISM, inhibiting star formation in the process. This agrees with recent suggestions of suppressed star formation in some systems with a weak radio jet, such as NGC 1266 (Nyland et al. 2013; Alatalo et al. 2015) and some molecular hydrogen emission galaxies with weak radio jets (Ogle et al. 2007, 2010; Lanz et al. 2015a).

As noted in Section 1, the radio luminosity function implies that the distribution of 1.4 GHz radio power, $P_{1.4}$, peaks at around the FRI/FRII break at $10^{24.6}$ W Hz$^{-1}$ (Mauch & Sadler 2007). Approximately this corresponds to $P_{\text{jet}} \sim 10^{42–43}$ erg s$^{-1}$. Thus, given our results from the simulation with $P_{\text{jet}} = 10^{43}$ erg s$^{-1}$, we expect that low-powered jets with $P_{\text{jet}} \lesssim 10^{43}$ erg s$^{-1}$ should play a significant role in affecting the evolution of the ISM and star formation in the host galaxy.
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which assisted us in improving the original manuscript. We acknowledge constructive comments by the referee, help and support in carrying out the simulations and subsequent analysis. We thank the HPC and IT teams at the National Computational Infrastructure, the ANU, the Pawsey Supercomputing Centre and RSAA for their support. We thank Matt Lehnert and Nicole Nesvadba for useful discussions. We thank Christoph Federrath, through the Discovery Project, The Key Role of Black Holes in Galaxy Evolution, DP140103341. We thank Christoph Federrath, Di Matteo T., Springel V., Hernquist L., 2005, Nature, 433, 604

ACKNOWLEDGEMENTS

This research was supported by the Australian Research Council through the Discovery Project, The Key Role of Black Holes in Galaxy Evolution, DP140103341. We thank Christoph Federrath, Matt Lehnert and Nicole Nesvadba for useful discussions. We thank the HPC and IT teams at the National Computational Infrastructure, the ANU, the Pawsey Supercomputing Centre and RSAA for their help and support in carrying out the simulations and subsequent analysis. We acknowledge constructive comments by the referee, which assisted us in improving the original manuscript.

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(iv) Efficiency of feedback:

the jet significantly couples to the ISM within the central few kpc before it breaks out into the ambient halo. From Fig. 19, we see that nearly ~30 per cent of the jet energy is transferred as kinetic energy to the ISM for high-power jets. This measure of coupling efficiency is independent of jet power and density, as long as the jet creates a sufficiently overpressured bubble. This agrees with previous results of WBU12.

(v) Small net mass-loss:

only a few per cent of the dense gas mass is ejected from the galaxy to large distances (see Fig. 20). Most of the mass affected by the energy bubble is expected to rain back down into the galaxy’s potential on free-fall time-scales – typically of the order of a few tens of Myr. This supports the galactic fountain scenario of jet-driven feedback (similar to Oppenheimer et al. 2010; Davé et al. 2012). The jets may cause temporary quenching of star formation by launching local outflows and making the ISM turbulent, but the ejected mass will fall back and may be available for star formation after a few tens of Myr. The effect of such repeated cyclic explosive episodes and its connection to the AGN duty cycle needs to be explored in future work.

\[ E_{\text{kin}} / P_{\text{jet}}, E_{\text{kin}} \text{ being the kinetic energy of the dense gas (} n > 1 \text{ cm}^{-3}) \]

\[ (v) \text{ Small net mass-loss: only a few per cent of the dense gas mass is ejected from the galaxy to large distances (see Fig. 20). Most of the mass affected by the energy bubble is expected to rain back down into the galaxy’s potential on free-fall time-scales – typically of the order of a few tens of Myr. This supports the galactic fountain scenario of jet-driven feedback (similar to Oppenheimer et al. 2010; Davé et al. 2012). The jets may cause temporary quenching of star formation by launching local outflows and making the ISM turbulent, but the ejected mass will fall back and may be available for star formation after a few tens of Myr. The effect of such repeated cyclic explosive episodes and its connection to the AGN duty cycle needs to be explored in future work.} \]

\[ E_{\text{kin}} / P_{\text{jet}}, E_{\text{kin}} \text{ being the kinetic energy of the dense gas (} n > 1 \text{ cm}^{-3}) \]
APPENDIX A: PROBABILITY DENSITY FUNCTIONS

The lognormal distribution has proven to provide excellent description of the density prPDF for simulations of isothermal turbulence (Li, Klessen & Mac Low 2003; Kritsuk et al. 2007; Federrath et al. 2010). The distribution is defined as a Gaussian in $s = \ln \rho$ with a mean $-\sigma_s^2/2$ and variance $\sigma_s^2$:

$$P_\nu(s) = \frac{1}{\sigma_s \sqrt{2\pi}} \exp \left[ -\frac{(s + \sigma_s^2/2)^2}{2\sigma_s^2} \right]$$  \hspace{1cm} (A1)

The subscript $\nu$ refers to volume-weighted PDF, which is considered primarily in this work while describing the 1D density PDFs. The above definition of the PDF satisfies the following two conditions of normalizations:

$$\int_{-\infty}^{\infty} P_\nu(\ln \rho) \, d \ln \rho = 1$$  \hspace{1cm} (A2)

$$\int_{-\infty}^{\infty} \rho P_\nu(\ln \rho) = \bar{\rho} \text{ (mean density).}$$  \hspace{1cm} (A3)

The mean of the distribution is

$$\langle \ln \rho \rangle = -\frac{\sigma_s^2}{2}$$  \hspace{1cm} (A4)

and the variance in $\rho$ is

$$\sigma_\rho^2 = \rho^2 \left[ \exp \left( \sigma_s^2 \right) - 1 \right].$$  \hspace{1cm} (A5)

In the presence of strong shocks, the density PDF shows significant departure from a true lognormal, especially in the high- and low-density tails. An improved function proposed by Hopkins (2013) gives a better description of the density PDF in the presence of intermittency:

$$P_\nu(s) = I_1 \left(2 \sqrt{\lambda u(s)}\right) \exp \left[-(\lambda + u(s))\right] \sqrt{\frac{\lambda}{u(s)\eta^2}}$$

$$u(s) = \frac{\lambda}{1 + \eta} - \frac{s}{\eta} \left( u \geq 0 \right); \ s = \ln (\rho/\bar{\rho})$$

$$\lambda = \frac{\sigma_s^2}{2\eta^2}.$$  \hspace{1cm} (A7)

Here, $I_1$ is the modified Bessel function of the first kind. The PDF in equation (A7) is defined by three parameters: the mean density $\bar{\rho}$ which is defined by A2, the dispersion ($\sigma_s$) and a parameter $\eta$ defining the degree of departure from a lognormality. For $\eta = 0$, 

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equation (A7) reduces to the standard expression of a lognormal distribution (equation A1). The mean density of the improved function is same as in equation (A4) above. The variance in $\rho$ is given by

$$\sigma_{\rho}^2 = \bar{\rho}^2 \left[ \exp \left( \frac{\sigma_{\gamma}^2}{1 + 3\eta + 2\eta^2} \right) - 1 \right].$$

(A8)

**APPENDIX B: ADIABATIC EXPANSION OF AN ENERGY BUBBLE**

For a spherical bubble with radius $R_B$, expanding with uniform pressure ($p_B$), driven by a constant input energy flux from a jet or wind ($P_j$), the energy equation can be written as

$$\frac{d}{dt} \left[ \frac{4\pi}{3} p_B R_B^3 \right] + 4\pi R_B^2 p_B \frac{dR_B}{dt} = P_j - L_{\text{cool}}$$

(B1)

$$\frac{d}{dt} [p_B R^{3\gamma}] = \frac{3(\gamma - 1)}{4\pi} P_j R_B^{3(\gamma - 1)},$$

(B2)

where $\gamma$ is the adiabatic index and $L_{\text{cool}}$ is energy loss from atomic cooling. The first term in the left hand side of equation (B1) is the change of internal energy inside the volume, while the second term is the work done by the expanding bubble. Since we are considering an adiabatically expanding bubble, we do not consider the cooling losses in equation (B2). If the radius expands as $R_B \propto t^\alpha$, following equation (B2), we find that the pressure to evolve as

$$p_B \propto t^{1-3\alpha}.$$  

(B3)

For a self-similarly expanding bubble in an ISM of constant density ($\rho_0$), the radius and pressure evolve as (Castor et al. 1975; Weaver et al. 1977)

$$R_B \propto \left( \frac{P_j}{\rho_0} \right)^{1/5} t^{3/5}; \quad p_B \propto t^{-4/5}.$$  

(B4)

However, in a multiphase ISM the bubble expansion is slower than the adiabatic case due to cooling losses and turbulent mixing (e.g. Rosen et al. 2014). For Fig. 11, we find the radius to evolve as $R_B \propto t^{0.55}$. For an adiabatically expanding bubble, this implies (following equation B3) that the pressure should vary as $p_B \propto t^{-0.65}$. This approximately agrees with the initial evolution of the mean pressure of the bubble (shown in Fig. 10), for the simulations with high-power jets ($P_{\text{jet}} \gtrsim 10^{44} \text{ ergs}^{-1}$). This indicates that for jets with higher power, an overpressured bubble is formed which initially evolves as an adiabatically expanding spherical bubble till jet break out.

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