The influence of the environment on the propagation of protostellar outflows

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ABSTRACT

The properties of bipolar outflows depend on the structure in the environment as well as the nature of the jet. To help distinguish between the two, we investigate here the properties pertaining to the ambient medium. We execute axisymmetric hydrodynamic simulations, injecting continuous atomic jets into molecular media with density gradients (protostellar cores) and density discontinuities (thick swept-up sheets). We determine the distribution of outflowing mass with radial velocity (the mass spectrum) to quantify our approach and to compare to observationally determined values. We uncover a sequence from clump entrainment in the flanks to bow shock sweeping as the density profile steepens. We also find that the dense, highly supersonic outflows remain collimated but can become turbulent after passing through a shell. The mass spectra vary substantially in time, especially at radial speeds exceeding 15 km s\(^{-1}\). The mass spectra also vary according to the conditions: both envelope-type density distributions and the passage through dense sheets generate considerably steeper mass spectra than a uniform medium. The simulations suggest that observed outflows penetrate highly non-uniform media.

Key words: hydrodynamics – stars: formation – ISM: jets and outflows.

1 INTRODUCTION

Bipolar outflows are associated with the early stages of the formation of stars with strong evidence for a direct connection to the inflow process through accretion discs (Calvet 2004). Many bipolar outflows have been studied since their first discovery a quarter of a century ago as traced in rotational emission lines of carbon monoxide (Snell, Loren & Plambeck 1980; Bally & Lada 1983). Currently, there is an observational bias towards large established flows but new technology at millimetre and near-infrared wavelengths is revealing a wealth of smaller and younger outflows, such as in the DR21/W75 region (Davis et al. 2007). Small parts are also often observed in the optical as Herbig–Haro (HH) objects which are created where strong shocks form within the outflow or at the leading edge where the outflow impacts against the surrounding medium (e.g. Bally et al. 2006).

A protostellar outflow usually takes a bipolar configuration with molecular gas receding from both sides of an obscured central object. Outflows are capable of maintaining high collimation over distances exceeding parsecs although quite uncollimated distributions are often found (Richer et al. 2000). Total outflow masses above 100 M\(_\odot\) are possible (e.g. Garay et al. 2007), implying that the material does not originate from the driving source but from the surrounding cloud. To drive such an outflow requires a source of considerable sustained momentum output.

There are currently three distinct theories which attempt to explain how such large amounts of material are set in motion. One involves a wide angle wind emanating from the accretion disc which sweeps up the ambient medium into a shell and is itself deflected in a momentum conserving fashion (e.g. Shu et al. 1991; Lee et al. 2001; Shang et al. 2006). The second scenario is the gradual entrainment of ambient material through a turbulent viscous mixing layer set up by Kelvin–Helmholtz instabilities as a jet streams past (Canto & Raga 1991). The third scenario is called the ‘prompt entrainment’ model. Here, a large bow shock is driven by a supersonic jet which is launched and collimated by magnetic fields (e.g. Raga & Cabrit 1993; Smith, Suttner & Yorke 1997; Rosen et al. 1999).

All the scenarios can explain some observed features but none is completely satisfying. One of the main problems associated with directed jet models is that they cannot produce the observed outflow widths. In the directed jet model, strong molecular cooling and a high Mach number limits the transverse expansion and the width is

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usually determined by the leading bow shock. In a uniform medium, if the axial propagation increases linearly with time, the transverse expansion increases only as $t^{1/3}$ (Lee et al. 2002). Problems with the wide-angle wind models are that they cannot create bow shock like features or the high degree of collimation of some observed flows (Lee et al. 2002). Additionally, the wind scenario cannot explain the fact that the highest radial velocities are found furthest from the driving source (Masson & Chernin 1993).

It can be argued that both mechanisms play cooperative roles (Shang et al. 2006). Perhaps over time as the accretion rate falls, the jet may weaken and the wind becomes the dominant driving mechanism. Alternatively, a wide-angle precession in the jet direction will also simulate most features of a wide-angle wind (Rosen & Smith 2004a).

We examine here the issues associated with the jet scenario. It is assumed that momentum is channelled from near the young star system via a jet into the surrounding ambient medium. The efficiency of momentum transfer has been a topic of recent debate and suggests that it may be too low to supply the bipolar outflows (Su, Zhang & Lim 2004). Cunningham et al. (2006) performed simulations investigating fossil cavities – outflows where the driving source has recently switched off. One of their findings is a scaling law which could be used to predict the momentum input into observed cavities from their sizes and velocities. We aim to calculate the physical structure of the flow and the momentum transferred as measured by the distribution of CO mass, $m$(CO), with radial velocity, $v_r$. The CO mass spectrum is quantified by fitting the equivalent power-law sections of the form $m$(CO) ~ $v_r^{-2}$ even when the power law is not appropriate.

It has been found from observations that numerous outflows appear to follow a so-called ‘Hubble law’, meaning that their velocity increases linearly with distance from the driving source ($v_r$ ~ $r$). This has also been noted in jet simulations of Smith et al. (1997) and Downes & Ray (1999). The latter noted that the Hubble law effect is associated with the bow shock and is a global phenomenon only if the bow shock acts as the interface with the ambient medium for the entire flow. In the wind model, the higher velocity further from the source could also be caused by an ambient medium whose density decreases in a power-law profile of the form $1/r^2$ (Shu et al. 1991).

It becomes clear that outflows contain as much information about the medium they disturb as the object which drives them. Hence, we need to develop means to decipher their signatures before we can gain insight into the deeply embedded young stellar object at their heart. We wish to distinguish the launch-induced properties from the environment-induced properties. Here, we will investigate numerically the influence the environment has on the outflow. This follows up on our previous works which have explored the influence of the driving source in terms of jet precession, pulsation, shear, speed and rotation, all into a uniform ambient medium (Smith & Rosen 2005; Moraghan, Smith & Rosen 2006; Smith & Rosen 2007).

There are two issues that require our attention. First, do we observe HH objects and molecular shocks because they are the present points of impact within and at the end of an impulsive jet? Or, do we only observe the locations where the outflow temporarily interacts with dense structures in the ambient medium? To probe this, we present three simulations containing clumps or filaments in the ambient medium for the jet to collide with. The clumps are represented here as thick sheets, aligned transverse to the jet axis (as the assumed cylindrical symmetry approximation allows).

Secondly, outflows from the youngest forming stars must still excavate through dense protostellar envelopes. These envelopes are believed to possess power-law density profiles. We ask here if there are specific signatures which can be related to the nature of the envelope. To probe this, we run simulations over a large power-law parameter space. We present four simulations to highlight the trends of changing the various parameters.

3D simulations of atomic jets into ambient media with power-law density profiles as well as large clumps have been presented by de Gouveia Dal Pino & Birkinshaw (1996) and de Gouveia Dal Pino (1999). Due to the high jet sound speed, the jet is poorly collimated. They noted that the expanding jet may oscillate in velocity. They also remarked that a jet interacting with clumps may inject a considerable amount of shocked jet material sideways into the ambient medium, providing a means to transfer momentum through turbulent mixing with the ambient medium.

The layout of our paper is as follows. We shall describe the additions we made to our computational code in order to aid our investigation in Section 2. Then we present our results in Section 4, describing the figure layouts, and divide the analysis between the core simulations, Section 5, and the dense clump simulations, Section 6. Finally, we discuss our findings with respect to observational results in Section 7.

## 2 Method

**ZEUS-3D** is a grid-based computational fluid dynamics code (Stone & Norman 1992). Its design allows for the simple insertion of additional physics modules. Our modified version expands on the base code by incorporating a module for molecular and atomic cooling using a semi-implicit scheme for calculating molecular and atomic hydrogen fractions. The module itself has been adopted from a version written by Suttner et al. (1997) and now includes improved routines with a limited equilibrium C and O chemistry to calculate CO, OH and H$_2$O abundances. Details and tests may be seen in the Appendices of Smith & Rosen (2003). The slightly revised code has been previously checked (Moraghan et al. 2006) and found to give acceptable agreement against the adiabatic and atomic simulations presented by Stone & Hardee (2000).

For this study we have further modified the code to incorporate an inhomogeneous ambient medium whose density falls off as a power law with distance from the source (the left-hand side of the grid). Comparable simulations have previously been performed by de Gouveia Dal Pino & Birkinshaw (1996) and Carvalho & O’Dea (2002) but only for radiatively cooled atomic flows and adiabatic extragalactic jets, respectively. Along similar lines, O’Sullivan & Lergy (2002) simulated an inhomogeneous ambient medium by inserting a step along the grid where the ambient medium changes from a molecular core composition to one of an interstellar medium.

We will also add sheets of dense molecular gas perpendicular to the jet axis. Many simulations of turbulence in star-forming regions (including those with molecular cooling and chemistry, Pavlovski et al. 2004) show that molecular clouds would be filled with filaments and sheets of denser material. Our modified code comes somewhat towards emulating such a system by allowing the simple inclusion of ‘clumps’ or slabs within the ambient medium.

Here, the entire jet and cocoon collides head-on and must tunnel through the sheets. This thick shell approach may emulate head-on collisions with large clumps, the crossing through of other outflows and their bow shocks or, assuming outburst episodes, may represent bow shocks from a previous ejection event from the same source or ‘fossil cavities’.
Simulations performed by Rossi et al. (2000) followed a similar approach of a jet colliding head-on with a density enhancement in 2D axisymmetry. Their work differed by dealing with radiative extragalactic jets and the enhanced density slabs representing giant molecular clouds.

The sound speed in the ambient medium is sufficiently low (~0.7 km s\(^{-1}\)) so that little dispersal of the envelope or sheets occurs. Therefore, we do not include any external force to maintain either the envelope density or the shell density profile. Strictly speaking, however, the sheets would correspond to the temporary features expected in a turbulent medium. The longevity of the sheets was carefully tested by modelling the ambient medium alone for thousands of years to investigate if there was a drifting of the higher density material to the lower. It was found to be negligible for the grid crossing times of all our jets. This can also be verified in the figures presented here which display the density profile of the ambient medium at the times indicated.

We study the jet propagation and assume that the jet has already been launched and collimated somewhere off the left-hand side of the grid. The detailed jet and environmental parameters, which are held constant unless otherwise indicated, are listed in Table 1. We follow the same set-up as Moraghan et al. (2006), i.e. 2.5D axisymmetric simulations on a grid of 4000 × 800 zones covering (2.5 × 10\(^{17}\) cm) × (5 × 10\(^{16}\) cm) in extent. The initial jet radius is \(R_j = 2.5 \times 10^{14}\) cm, leading to 40 zones per jet radius, 100 jet radii in the axial direction and 20 jet radii in the radial direction. Again, magnetic fields have been omitted as we are only focusing on the effect of the ambient medium on the outflow.

In this paper, we focus on one particular set of initial jet conditions: the 100 km s\(^{-1}\) atomic jet into a molecular ambient medium (the AJMA jet in Moraghan et al. 2006). The jet is overdense with respect to the ambient medium by a factor of \(\eta = \rho_j/\rho_s = 10\). The molecular hydrogen abundance in the ambient medium is set to 0.5 (fully molecular) and in the jet beam the molecular fraction is reduced to 10\(^{-5}\) with the carbon and oxygen abundances remaining as 10\(^{-4}\). This ensures that only the atomic radiative cooling approximation controls cooling in the jet.

By taking an atomic jet, we are able to explain bipolar outflows which possess high values of the mass–velocity power-law index, \(\gamma\) (Moraghan et al. 2006). However, we hereby exclude the presence of high-velocity CO along the main jet axis, as is sometimes observed (see Downes & Ray 1999). Although molecule formation can occur in the encoded physics, the jet material remains atomic due to the low density. On the other hand, the lack of a detectable high-velocity jet component in most mass–velocity observations may be attributed to the absence of molecules in the jet beam itself. However, it could also be explained if the molecular jet beam possesses velocity variations and, thus, the jet contribution is spread over the full velocity range. This concept will be investigated in a later publication.

### Table 1. Summary of the parameters of our set-up.

<table>
<thead>
<tr>
<th>Property</th>
<th>Jet</th>
<th>Ambient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (gm cm(^{-3}))</td>
<td>2.342 × 10(^{-21})</td>
<td>2.342 × 10(^{-22})</td>
</tr>
<tr>
<td>Specific energy (erg cm(^{-3}))</td>
<td>2.278 × 10(^{-10})</td>
<td>1.933 × 10(^{-12})</td>
</tr>
<tr>
<td>(n(H_2)/n)</td>
<td>1.0 × 10(^{-5})</td>
<td>0.5</td>
</tr>
<tr>
<td>Specific heat ratio, (\gamma)</td>
<td>1.6667</td>
<td>1.42857</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>1000</td>
<td>100</td>
</tr>
<tr>
<td>Sound speed (km s(^{-1}))</td>
<td>3.29</td>
<td>0.71</td>
</tr>
<tr>
<td>Mach number, (M_{jet})</td>
<td>30.42</td>
<td>140.67</td>
</tr>
</tbody>
</table>

### Table 2. Summary of the parameters for the ambient medium density profiles. \(\chi\) represents the power-law exponent and \(\Psi\) represents the size of the ‘core’ region defined by equation (1).

<table>
<thead>
<tr>
<th>Profile</th>
<th>(\chi)</th>
<th>(\Psi) (cm)</th>
<th>(\Psi) (zones)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.0</td>
<td>1.250 × 10(^{17})</td>
<td>2000</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>6.250 × 10(^{16})</td>
<td>1000</td>
</tr>
<tr>
<td>3</td>
<td>1.5</td>
<td>3.125 × 10(^{16})</td>
<td>500</td>
</tr>
<tr>
<td>4</td>
<td>2.0</td>
<td>3.125 × 10(^{16})</td>
<td>500</td>
</tr>
</tbody>
</table>

Our ambient medium density profile nearly follows the form of a King profile:

\[
d(i) = \frac{d_s}{1 + [x(i)/\Psi]^\chi},
\]

where \(d(i)\) and \(x(i)\) are the density and position, respectively, along the x direction (the jet axis) expressed in zones, \(d_s\) is the initial ambient medium density (see Table 1), \(\Psi\) is the size of a relatively uniform ‘core’ or plateau region at the beginning of the grid and \(\chi\) is the power-law exponent. We found that the \(\chi\) and \(\Psi\) parameters are intrinsically linked and must both be carefully controlled in order to obtain sensible profiles. Fig. 1 displays the four profiles used in the envelope simulations presented here and Table 2 lists the parameter space covered.

### 3 MASS–VELOCITY SPECTRA

Mass–velocity distributions are frequently used to explore how momentum is transferred from the jet to the ambient medium. They are approximated by the function \(dn/du_r \propto u_r^{-\gamma}\). Observationally, the mass, \(m\), is deduced from the intensities of low rotational optically thin CO spectral lines (e.g. Yu et al. 2000). Very often, observations show broken power laws, consisting of two distinct sections. A shallow slope is found at low velocities connected to a steeper one at high velocities by a ‘break point’. Careful ambient cloud subtraction is necessary to correctly estimate the low-velocity component (Yu et al. 2000; Arce & Goodman 2001). This can be clearly seen in figs 13 and 14 of Yu et al. (2000) where two slopes with a break point are revealed after the ambient cloud subtraction. In bow shock theory, the break velocity may correspond to the projected component of the molecular dissociation velocity.

Mass–velocity plots from simulations are easier to obtain than observations as there is no confusion or uncertainty from factors such

![Figure 1. Plot showing the four ambient medium density profiles used in our protostellar core simulations superimposed for comparison purposes and labelled Profile 1–4, the parameters of which being displayed in Table 2.](https://academic.oup.com/mnras/article-abstract/386/4/2091/1462429 by guest on 03 January 2019)
as optical depth, ambient cloud motion or overlap with other flows. Values for $\gamma$ have been predicted from various simulations and almost always found to be dependent on the viewing angle (e.g. Rosen & Smith 2004b). This is due to the fact that the viewing angle stretches or compresses the velocity range while holding constant the range of mass between the two velocity extrema. Recently, Smith & Rosen (2007) found that jet rotation leads to a lower value of $\gamma$.

Shallow spectra ($\gamma < 2$) were predicted in works by Smith et al. (1997), Downes & Cabrit (2003) and Keegan & Downes (2005). The latter performed long-duration simulations to find that $\gamma$ does not increase indefinitely but eventually levels out after 1500 yr. Wind driven outflows, as opposed to jet driven outflows, were found to lead to smaller $\gamma$ values in Lee et al. (2001).

Mass spectra with intermediate slopes ($2 < \gamma < 4$) were found by Downes & Ray (1999). They also noted an increase of $\gamma$ with decreasing jet molecular abundance. This suggests that most jets may be atomic, the case explored here. Taking an atomic jet also allows us to easily reduce the jet contribution towards the total molecular mass in motion by a factor of $10^3$ to effectively only count ambient material set in motion. (The total mass in motion is plotted as the dotted line on the mass–velocity profile plots.)

Steep mass spectra ($\gamma > 4$) along the full velocity range are not found in numerical simulations but can be noted in some simulations at the higher radial velocity region of the spectra. This leads to two distinctive slopes separated by a viewing angle-dependent break point as is commonly observed.

A peak in the mass spectra corresponding to the jet radial velocity is rarely found. These cases correspond to some flat mass spectrum outflows, suggesting that the jet CO pours out into the bow shock and contributes to the power-law section.

We calculate the resultant mass–velocity $\gamma$ values across four fixed velocity ranges: $2$–$4$, $4$–$8$, $8$–$16$ and $16$–$32$ km $s^{-1}$, hereafter referred to as velocity intervals ‘A’, ‘B’, ‘C’ and ‘D’, respectively. This leads to objective values of $\gamma$ which are automatically calculated during the simulations and can be compared directly with other runs and viewing angles. The slope values determined over the four intervals are displayed on the diagrams.

4 RESULTS: COMPOSITE FIGURES

The multifaceted visualizations of the main runs shown in Figs 2–5 present the following information. (Colour plots are available in the electronic version.)

(i) The first panel displays the total mass density in g cm$^{-3}$ on a logarithmic scale with the corresponding scale bar to the right-hand side. The simulation ‘age’ is shown in years.

(ii) The second panel displays the temperature in degrees kelvin, again on a logarithmic scale with the scale bar displayed on the right-hand side. The figure is flipped by $180^\circ$ to aid in visualizing the entire jet.

(iii) The third panel shows the molecular fraction or, in other words, the ratio of hydrogen molecules to the total number of hydrogen nuclei $[n(H_2)/n]$. It is on a linear scale from 0 (completely atomic) to 0.5 (fully molecular).

(iv) The fourth panel displays the pressure in erg cm$^{-3}$ on a logarithmic scale.

(v) The fifth and sixth panels display the axial ($v_1$) and radial ($v_2$) velocities, respectively, in km s$^{-1}$. Interestingly, negative $v_2$ velocities can be seen signifying motion towards the jet axis. This shows turbulent mixing/entrainment along the cocoon.

(vi) The seventh panel is a graph of the density profile of the undisturbed ambient medium (solid line) along the full axial extent of the grid ($x$-axis in the plots). The ‘log(density)’ axis label signifies mass density in g cm$^{-3}$ on a logarithmic scale. The corresponding jet beam (dashed line) density profile is shown at a radial distance of 0 ($y$-axis in the plots). The $\chi$ and $\Psi$ parameters for each core simulation are printed to help aid identification.

(vii) The bottom detached panel is a plot of the $\gamma$ values as a function of time. The line thickness represents the radial velocity intervals, ranging from the thickest line for the fastest (‘A’ and ‘B’) intervals to the thinnest line for the slowest (‘C’ and ‘D’). They are additionally colour coded in the electronic version against the final instantaneous mass spectrum display to the right-hand side. These plots were obtained with the aid of an additional modification to the ZEUS code. This modification calculates and outputs the mass–velocity spectrum at intervals of one year during the simulation. Animations of the data thus allow us to precisely follow the evolution of the mass–velocity profile as the outflow propagates across the grid.

(viii) The instantaneous end-of-run mass spectra are plotted in the bottom right-hand panel. All the spectra are displayed for a 45$^\circ$ viewing angle out of the planet of the sky. The $\gamma$-axis scale is in units of the logarithm of solar mass per kilometre per second, log ($M_\odot/(km s^{-1})$).

The solid line shows the molecular mass in motion while the dotted shows the total grid mass in motion, both representing blueshifted material towards our line of sight. The vertical dashed lines divide the spectra into the four radial velocity regions: ‘A’, ‘B’, ‘C’ and ‘D’ (see Section 3). The slope of the molecular mass spectra within the intervals is printed near the top of the plot. (In the electronic version, these values are colour coded to the lines of the $\gamma$ versus time plot.) The sharp peaks in the total mass spectra represent the jet beam material at a radial velocity, $|V_{rad}|$, or $v_{jet} \sin \alpha$ whose log value is 1.85 for our 100 km s$^{-1}$ jets.

The simulations were initially run at low resolution to explore a wide area of parameter space. Several resolutions were then employed to check that convergence in the results was occurring within the expectations for a turbulent flow. The surprisingly strong and rapid temporal variability in $\gamma$ was noted. Selected runs were then rerun at high resolution to provide the figures displayed here as Figs 2–5.

Ambient density ‘clump’ simulations are shown in Figs 4 and 5. They consist of various configurations of slabs or sheets within the ambient medium.

5 PROPAGATION OUT OF CORES

5.1 Flow structure

The initial density profile of the ambient medium follows a sequence as shown in Fig. 1. It is apparent that the sequence corresponds to a trend in the turbulent density structure from Fig. 2 (left-hand side) to Fig. 3 (right-hand side), as follows.

(1) The jet flowing through the plateau core of Fig. 2 (left-hand side) generates a turbulent interface in the inner region. However, a smooth shell is produced around the leading bow which has exited the plateau.

(2) The smooth shallow gradient taken in Fig. 2 (right-hand side) yields the opposite result. The expanding jet interacts stronger with the outer regions, and the turbulent interface is located in the leading half of the flow. The turbulence is portrayed in the velocity components as well as the density.
Figure 2. The outflow structures for the simulations of the plateau density profile, Profile 1 (left-hand side), and the smooth shallow gradient, Profile 2 (right-hand side); both as given in Table 2 and illustrated in Fig. 1. See Section 4 for full figure explanation.

(3) The structure of Fig. 3 (left-hand side) is generated by a moderate density gradient. The density shell contains only weak turbulence but does contain a large vortex.

(4) The steep density profile of Fig. 3 (right-hand side) produces a very smooth interface. There is no sign of turbulence or large vortices.

These effects are correlated with the density, temperature and pressure profiles. Turbulence is not created in Fig. 3 (right-hand side) corresponding to Profile 4 because a hot atomic cavity can expand laterally into the lower density surroundings. The rapidly falling ambient pressure and the wide cavity protects the jet from pressure feedback from the ambient gas. As a result the jet continues to...
propagate ballistically (see the conical structure of the axial velocity, v1), expanding laterally at a small constant rate. The jet and ambient material flows into the cavity at speeds approaching 40 km s\(^{-1}\). The cavity is filled with hot low-density atomic gas at around 10\(^4\) K.

In contrast, with a shallow gradient, the ambient and jet pressures become comparable (Fig. 2, right-hand side). The jet is slightly deflected towards the axis and the highest pressure of all four simulations occurs at the impact location or terminal shock. The cavity contains warm atomic gas at ~10\(^4\) K.

Returning to the plateau core (Fig. 2, left-hand side), the turbulence takes the form typical of a mixing layer brought on by the Kelvin–Helmholtz instability. This was also revealed in the simulation AJMA where a uniform environment was taken. This demonstrates that a turbulent cocoon is not only caused by a ‘clumpy’ ambient environment.

An intrinsic feature associated with all the jets presented here is that after propagating about 1000 zones, the jet density begins to fall (observe the dashed lines on the graphical profiles of the seventh panels). This is due to the propagation of a rarefaction wave from the jet beam surface to the central jet beam axis at the sound speed. As the jet beam is supersonic, this sound signal travels inward with a Mach angle of about 3\(^\circ\). The differing rates of the decreasing ambient density between the runs do not have a noticeable effect on the central jet expansion. It does however effect the expansion rate of the cocoon with Profiles 3 and 4 having a smaller length to width ratio compared to Profiles 1 and 2.

The molecular fraction panels of Fig. 2 show a clear division between shocked jet beam and shocked bow shock material. Entrainment is seen to occur in discrete clumps via fluid dynamic instabilities along the flanks (along with entrainment and strong dissociation around the front leading edge). In contrast, the broader bow shock wings of Fig. 3, intercept and partially dissociate a higher fraction of the ambient molecular gas over wide areas. Thus, our steep profile run in Fig. 3 (right-hand side) resembles the shape of the simple bow shock models of Raga & Cabrit (1993) suggesting pure bow shock entrainment. Finally, note that the radial extent of the shocked jet beam material in the cocoon remains roughly constant for each profile.

Are steeper profiles more efficient at setting mass in motion? Although the steeper profiles generate broader shocks that intercept a large volume of molecular gas, Table 3 demonstrates that both the total moving mass and moving molecular mass actually decreases for steeper profiles. Hence, less mass is being swept up despite the cavity volume appearing larger. Similarly, the same is true for the momentum values. It is clearly a trade off between cocoon width and the ambient medium density. Lower ambient densities lead to a wider flow but with less mass to entrain. Higher densities lead to a more collimated outflow where the mass entrainment is mainly through the terminal bow shock.

Corrected for outflow age and moving from Profile 1 to 4 we find the following.

(i) The entire grid mass drops by about 2.5 orders of magnitude yet the total moving mass fraction only decreases by about 20 per cent.

(ii) The total mass momentum decreases by 45 per cent yet the molecular momentum decreases by a much larger amount, 120 per cent.

This suggests that the steeper the profile, the less efficient the sweeping up of molecular ambient material becomes. The cavity increasingly consists of processed atomic jet beam material. Less molecular mass is entrained despite the larger inflated bow shocks.

The fraction of injected mass/total moving mass increases as the profiles become steeper. In all the runs, jet beam material is injected on to the grid at a steady rate of 7.295 × 10\(^{-9}\)M\(_\odot\) yr\(^{-1}\) but less grid moving mass leads to larger fractions. With these smoothly varying profiles, however, the fraction remains in a small range between 0.7 and 0.8.

Note that the ‘moving mass’ is defined with a lower limit of 3 km s\(^{-1}\) since it would be difficult to distinguish between general cloud turbulent motion and outflow motions at lower velocities.

### 5.2 Mass spectra analysis

The time evolution of the mass spectra as well as the final mass spectra is displayed in the figures for each run. The chosen angle to our line of sight is 45\(^\circ\). The major result is the strong and rapid variability of the characterizing γ indices for radial speeds exceeding ~4 km s\(^{-1}\). However, for low radial speeds (thin black line on evolution plots), the indices remain quite constant and relatively flat (close to unity). This implies that most of the mass set in motion possesses speeds of a few km s\(^{-1}\). Most of the momentum is contained in the gas moving at speeds exceeding ~4 km s\(^{-1}\).

The time-scale of the variation corresponds to that associated with large-scale changes to the leading bow shock. The jet dynamical time-scale, r\(_{jet}\)/v\(_{jet}\) is ~8 yr while the bow dynamical time-scale is taken as r\(_{bow}\)/v\(_{2max}\) where we take the bow size as r\(_{bow}\) = 10\(^{10}\) cm and the maximum transverse speed v\(_{2max}\) = 30 km s\(^{-1}\) to give ~100 yr.

All the runs possess a small CO mass–velocity peak lying between a radial velocity of 45–55 km s\(^{-1}\). This is due to entrained ambient material in the working surface behind the bow shock. At certain times the working surface material gets expelled into the cavity as a vortex. This phenomenon can be seen to have just occurred in

<table>
<thead>
<tr>
<th>Run</th>
<th>Entire grid mass (M(_\odot))</th>
<th>Total moving mass over 3 km s(^{-1}) (M(_\odot))</th>
<th>H(<em>2) mass (M(</em>\odot))</th>
<th>Total mass momentum (M(_\odot) km s(^{-1}))</th>
<th>H(<em>2) momentum (M(</em>\odot) km s(^{-1}))</th>
<th>H(_2) mass/total mass</th>
<th>H(_2) mom/total mom</th>
<th>Injected mass/total moving mass</th>
<th>Uniform H(_2) mom/ run H(_2) mom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile 1</td>
<td>1.31(−4)</td>
<td>1.04(−5)</td>
<td>1.88(−6)</td>
<td>4.85(−4)</td>
<td>1.37(−5)</td>
<td>0.182</td>
<td>0.028</td>
<td>0.704</td>
<td>0.37</td>
</tr>
<tr>
<td>Profile 2</td>
<td>9.99(−5)</td>
<td>1.02(−5)</td>
<td>1.17(−6)</td>
<td>4.87(−4)</td>
<td>8.78(−6)</td>
<td>0.115</td>
<td>0.018</td>
<td>0.712</td>
<td>0.23</td>
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<tr>
<td>Profile 3</td>
<td>5.59(−5)</td>
<td>7.99(−6)</td>
<td>6.11(−7)</td>
<td>4.36(−4)</td>
<td>3.94(−6)</td>
<td>0.076</td>
<td>0.009</td>
<td>0.822</td>
<td>0.11</td>
</tr>
<tr>
<td>Profile 4</td>
<td>4.82(−5)</td>
<td>7.55(−6)</td>
<td>4.99(−7)</td>
<td>4.35(−4)</td>
<td>3.40(−6)</td>
<td>0.066</td>
<td>0.008</td>
<td>0.870</td>
<td>0.09</td>
</tr>
<tr>
<td>Multiple clump</td>
<td>7.22(−4)</td>
<td>3.11(−5)</td>
<td>1.96(−5)</td>
<td>6.54(−4)</td>
<td>1.78(−4)</td>
<td>0.63</td>
<td>0.28</td>
<td>0.33</td>
<td>4.75</td>
</tr>
<tr>
<td>Single clump</td>
<td>4.01(−4)</td>
<td>1.86(−5)</td>
<td>8.49(−6)</td>
<td>5.26(−4)</td>
<td>7.26(−5)</td>
<td>0.46</td>
<td>0.14</td>
<td>0.43</td>
<td>1.94</td>
</tr>
<tr>
<td>Extended clump</td>
<td>1.21(−3)</td>
<td>3.25(−5)</td>
<td>2.28(−5)</td>
<td>5.38(−4)</td>
<td>1.62(−4)</td>
<td>0.70</td>
<td>0.30</td>
<td>0.27</td>
<td>4.32</td>
</tr>
<tr>
<td>Uniform</td>
<td>2.39(−4)</td>
<td>1.51(−5)</td>
<td>5.08(−6)</td>
<td>5.32(−4)</td>
<td>3.75(−5)</td>
<td>0.34</td>
<td>0.07</td>
<td>0.53</td>
<td>1</td>
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</table>

Table 3. Comparison of the mass and momentum values of our runs at their end of grid configurations, including information from fig. 5 (right-hand side) of Moraghan et al. (2006). In the eighth and tenth columns, ‘momentum’ is abbreviated to ‘mom’.
Fig. 3 (left-hand side) where the shaded vortex has slowed to a radial velocity of 16 km s$^{-1}$. Its strength in the mass–velocity plot dampens as it propagates to slower $v_{\text{rad}}$ before finally being absorbed within the low-velocity mass reservoir. The vortex shedding events also appear on the $\gamma$ evolution plots in the intervals ‘C’ and ‘D’ which display corresponding peaks and troughs at simultaneous evolution times.

The $\gamma$ values for material with radial speeds 16–32 km s$^{-1}$ generally display the strongest variability, $\gamma$ reaching values in excess of 4 for short periods. The variability is correlated with the turbulence. In the plateau core, strong variability is present after just a few hundred years. With the shallow gradient (Fig. 2, right-hand side), the variations start after 500 yr, coinciding with the development of the vortices. Note that at first, this generates a quite flat index of $\gamma \sim 1$ at 600–700 yr, caused by the initial development of a large vortex. Once the vortex is transferred to the cavity interface where turbulence then develops, the spectrum then steepens. Note that this behaviour appears to be present but less dramatic in the following runs with steeper density profiles. While there is less turbulence in these runs, there is a mild interaction with the jet.

The mass spectra referred to above is the CO mass spectra, related to observations. Note that the total mass spectra (dotted line) is much flatter. Not only does the jet contribute to this (see the spike on the dotted lines on the right-hand panels) but the atomic flow into the cavity generates a very flat profile. Hence, to obtain a steep profile we require an atomic jet or a means to dissociate the molecules before they enter the cavity.

Furthermore, there is no obvious general trend in the simulations for steepening or flattening with time – depending on the precise conditions, and the particular time of observation, almost any mass spectrum can be observed. The average overall $\gamma$ value can be seen to generally slowly increase over time beneath the fluctuations of the fastest two $\gamma$ intervals (‘C’ and ‘D’) in the intermediate and steep profiles (see Fig. 3). The slower two $\gamma$ intervals (‘A’ and ‘B’) tend to remain constant but the more turbulent the cocoon becomes (i.e. in a less steep density gradient run), the fluctuations translate back to the slower intervals and lead to a general rise in those intervals. A noticeable example of this can be seen after 600 yr of propagation in the shallow envelope run of Fig. 2 (right-hand side) where $\gamma$ in interval ‘A’ is increasing slowly.

The long-duration simulations of Keegan & Downes (2005) found that for velocities over 20 km s$^{-1}$, there were substantial variations of $\gamma$, while for velocities below 20 km s$^{-1}$, the $\gamma$ value became constant. This is in agreement with our results where we find little variation in our slow ‘A’ and ‘B’ radial velocity intervals.

6 PROPOSITION THROUGH SHEETS

6.1 Flow structure

We may expect that impacts with dense sheets would disrupt the bow shock and cavity sufficiently to alter the mass spectrum. We display three such simulations here, all with sheets fifteen times denser than the ambient medium. The density profiles are again displayed in the seventh panel of the following figures. Although the sheets are 1.5 times the initial jet density, they are somewhat denser than the impinging jets at the point of impact due to jet expansion. Fig. 4 displays flows in which three sheets (left-hand side) and one sheet (right-hand side) of thickness $1.25 \times 10^{16}$ cm cut across the grid. The results of a simulation with three sheets of thickness $3.125 \times 10^{16}$ cm is displayed in Fig. 5. Note that the sheets are not pressure confined and the edges of the sheets expand at the sound speed due to a rarefaction wave. In 1000 yr, the wave will propagate 10 zones, as shown.

Prominent effects occur along the flanks of the outflow. Impacts with the clumps lead to temperatures over 200 000 K along the edges.

Figure 4. The outflow structures for the density discontinuity runs of the multiple clump simulation (left-hand side) and the single clump simulation (right-hand side). See Section 4 for full figure explanation.
As expected, this leads to strong turbulence, especially notable in the distribution of the molecular fraction. The turbulence entrains the molecular mass which reaches high velocities.

The presence of the clumps clearly pinch or focus the outflows, suppressing the low-density cavity from lateral expansion and forcing material towards the axis as seen by the negative radial velocities (e.g. at the second clump in Fig. 5). A similar effect was found in the 3D simulations by Cerqueira & de Gouveia Dal Pino (2001) of jets propagating into ambient media of increasing density and pressure. The authors noted that the low-pressure cocoons get compressed and the leading bow shock structure gets destroyed.

The clumps have invoked a much more turbulent cavity/ambient medium interface. This has led to a greater amount of molecular material in motion than compared to a similar uniform ambient medium simulation. However, the increases shown in Table 3 are commensurate with the additional mass available on the grid to be accelerated. Nevertheless, the higher fractions of $\text{H}_2$ momentum and moving mass result from the expected increase in transfer efficiency of these quantities in flows which are not driven by ballistic (overdense) jets.

The sheets thus produce a significant molecular/total moving mass fraction $[0.70$ for the extended clump run compared to $0.18$ for the plateau core (Profile 1)]. Furthermore, the majority of the total momentum derives from molecular momentum with significantly higher molecular/total momentum fractions when compared to the ‘core’ runs ($0.3$ for the extended clump run compared to $0.03$ for the plateau core).

Each of the clump simulations possess different outflow crossing times (displayed in the figures). Surprisingly, the outflow of the extended three-clump simulation (extended clump) crosses the grid faster than in the narrow three-clump simulation (multiple clump). Thus the focusing can be more important than the inertia of the sheets. Despite the extended clumps run possessing the greatest grid mass, and both the greatest moving total and $\text{H}_2$ masses, the multiple clump run possesses the greatest momentum. This suggests that if clumps are too large they would have a detrimental effect on momentum transfer. The $\eta$ value ($\rho_j/\rho_a$) drops accordingly from the initial overdense 1.5 value. For both the multiple clump and extended clumps runs, $\eta$ in the first clump equals 0.66, at the second clump $\eta$ equals 0.13 and in the third clump $\eta$ equals 0.04. The jet thus becomes a ‘light jet’ within the clumps ($\rho_j/\rho_a < 1$).

6.2 Mass spectra analysis

Collisions with the sheets lead to large fluctuations in $\gamma$. The evolution plots of Figs 4 and 5 show an abrupt increase in the highest velocity $\gamma$ interval, interval ‘D’, as the jet impinges on the first clump. Hence, the highest velocity bow shock material is rapidly decelerated by the high-density sheet. This steepening propagates back to the slower velocity intervals while being damped by the greater quantity of material at the lower velocities (visible in available movies), in a more extreme fashion to the vortex shedding events discussed for the core profile runs.

Comparing the $\gamma$ versus time plots of Fig. 4 (left- and right-hand sides) and Fig. 5 we see that the collision with a single clump is sufficient for a persistent fluctuation of the high-velocity component $\gamma$ profile. The suppression of the high-velocity $\gamma$ component remains in the multiple clump run where the front of the jet fails to have sufficient time to reform a stable high-velocity bow shock. However, the difference in this case is that the further collisions feed back to the slower velocities intervals and lead to fluctuations in those $\gamma$ components instead.

Overall, the presence of sheets can lead to higher $\gamma$ values compared to the core simulation values. The high-velocity $\gamma$ component reaches as high as 6–7.5 for the initial collision in the clump runs whereas the core runs do not rise above a $\gamma$ of 5.

7 CONCLUSIONS

Information about the cold environments which harbour young stars can be extracted from millimetre observations, employing dust and molecular tracers. However, the young stars drive bipolar outflows which alter the environment and possess distinct observational signatures. These signatures contain information about the interaction with the environment as well as the driving star. Our purpose here has been to use the high resolution afforded by 2D hydrodynamic simulations to explore the interaction.

Protostellar cores have been simulated here as smooth density profiles. With uniform or gradual density decreases, possibly corresponding to the youngest protostars, the outflow structures are narrow with turbulent entrainment of clumps along the flanks. Steeper density profiles, which may correspond to ageing young stars, are dominated by the leading bow shocks which entrain by ploughing through ambient gas.

The environments may also be pervaded by a pattern of dense filaments or sheets. Outflow maps may be dominated by the locations where the outflow impacts or cuts through sheets, where the majority of the material is accelerated and excited. Here, we have shown that a collimated outflow can become turbulent after passing through a shell.

The mass spectra corresponding to the molecular component vary substantially in time, especially at radial speeds exceeding 15 km s$^{-1}$. The $\gamma$ index increases sharply as a jet impinges on a sheet, followed by a gradual return to a shallower spectrum. The index also strongly varies in simulations dominated by the shedding of large vortices.
Our mass spectra provide a link to observationally obtained mass spectra. In general, our $\gamma$ values lie between 0.8 and 4 with steeper slopes towards the high-velocity end, in keeping with observations. We thus find general agreement with published values. The simulations suggest that the preponderance of observed outflows with high $\gamma$ values is evidence that the jets penetrate highly non-uniform media.

The mass spectra generated by interactions with shells display relatively small differences between molecular mass and total mass profiles. Hence, in flows dominated by transverse interactions, the molecular mass is representative of the total mass. However, in the case of core-type density distributions, there are always large discrepancies between CO-derived line profiles and the underlying total mass distribution. The difference is mainly at speeds in excess of 20 km s$^{-1}$ and is thus related to the leading edge of the bow shock where molecules suffer a wholesale dissociation.

The total mass in these outflows (column 2 of Table 3 are many orders of magnitude less than observationally obtained values. One reason is that our simulated outflows are relatively young. Real outflows have dynamical time-scales of the order of $10^3$–$10^5$ yr. Scaling our 1000-yr $10^{-5}$ M$\odot$ outflows by 100 and doubling for bipolarity, we still obtain relatively less massive outflows. We have also assumed low jet densities in order to better resolve radiative cooling and molecular chemistry. The densities of jets associated with Class 0 protostars may be 1000 times higher.

It should also be noted that a strong magnetic pressure in the jet would promote jet expansion, generating wide outflows. The magnetic field in the ambient medium may also cushion the shock waves, leading to significantly less dissociation. Recent axisymmetric magnetohydrodynamics (MHD) jet simulations were performed by de Colle & Raga (2006). These confirmed previous findings that the tension created by a toroidal magnetic field tends to collimate the spine of the jet and produce a nose cone. Considering this morphlogy, we may expect shallower mass–velocity plots and lower $\gamma$ values as cavity material is focused close to the high speed jet beam thus leading to an increase in high-velocity components combined with less ambient medium entrainment from the bow shock.

Our simulations suggest that observational break points in mass spectra are controlled by large vortex features in the cavity. Sharp break points at low radial velocities do not occur in our simulations. The time evolution plots suggest break points, such as shown in Fig. 3 (left-hand side), are transient features created by large vortex shedding events. Fig. 2 (right-hand side) shows no noticeable break point.

Fig. 4 (left-hand side) shows a break point at a radial velocity of 25 km s$^{-1}$ where a small velocity peak exists. As we see in animations, this velocity peak will propagate back to the slower mass–velocity intervals with time, effectively dragging the apparent break point back with it.

Sharp break points may indicate that the outflow impacts with ambient clumps or episodic outflows are generating new large vortices. We may thus predict particularly bright HH objects from such mass spectra. Looking for large differences between high and low-velocity $\gamma$ in studied outflows, we find large differences for NGC 2264G and G192.16, both associated with strong shock activity (Shepherd et al. 1998).

We conclude that mass spectra of protostellar outflows cannot be used to derive information about the driving source due to a strong dependence on the ambient medium. Even the total momentum delivered into the ambient molecular medium can vary by an order of magnitude, according to the nature of the interaction which is stronger for higher densities (lighter jets) and more clumpy density distributions, as expected. Steep ambient medium density profiles are extremely inefficient at transferring momentum both compared to a ‘clumpy’ environment and a uniform one.

The study presented here unites the results of other studies which have focused on specific simulations. Recent work by Banerjee, Klessen & Fendt (2007) of turbulence in molecular clouds has shown, in 2D slab jet simulations, that a transient jet can completely disperse a higher density clump of material through which it moves, thus effectively transferring momentum. Carvalho & O’Dea (2002) noted less structure in the cocoon due to lack of turbulence in their declining density atmosphere runs, as we have found in our steep profile runs.

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