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The influence of a surrounding wind on overpressured jets – I. Subsonic winds

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ABSTRACT

There is evidence that supersonic jet flows in astrophysics are accompanied by surrounding slow winds. This is analogous to the flow past jet engines when an aircraft is in flight. If the jet itself enters the medium underexpanded, there will be a distinct flow pattern as the wind is deflected by the diverging jet. Here, we explore the general problem of such an overpressured jet flow encompassed by a wind which is subsonic. We simulate the long-term adjustment by performing a series of hydrodynamic adiabatic gas experiments in two dimensions with cylindrical symmetry. The major result is that the oscillations in the jet induced by feedback are suppressed once the wind has swept clean the initial jet overspill. Therefore, a slow ambient wind reduces the noise caused by the exhaust and may fully stabilize jet propagation. The differences between the shock diamonds of regular reflection and Mach discs are elucidated. In particular, with a wind, a distinctive pattern of repeated Mach shock discs occurs at high overpressures that replaces the turbulent plume. Secondly, the presence of a faster subsonic wind generates central enhanced pressure arcs and knots within each diamond. These features could provide indirect evidence for winds and are briefly discussed in terms of potential consequences for star and galaxy formation.

Key words: hydrodynamics – shock waves – stars: jets – ISM: jets and outflows – galaxies: jets.

1 INTRODUCTION

There is considerable renewed interest in the field of overpressured jets. This is because the study of the continued release of high-pressure gas from an orifice in a wall has implications for nuclear safety (J. Huang et al. 2025) and fuel injection (F. Duroño & A. Di Mascio 2025). However, in astrophysics and aerodynamics, the jet, rather than issuing from a solid boundary, may be encompassed by a wind blowing past the nozzle. This may be envisaged as a disc wind (M. N. Simon et al. 2016; C. J. R. Lynch & M. D. Smith 2020; A. Wang et al. 2023; I. Pascucci et al. 2025; C. Vleugels et al. 2025) or a galactic wind (N. Roy et al. 2024). The jet originates from the vicinity of a protostar or active galactic nucleus. Hence, it is appropriate to investigate what signatures could be attributed to the existence of an extended wind. In this first study, we explore the effect of a wind that is subsonic running parallel to the jet flow. This is akin to the flow downstream of a jet engine of an aircraft in subsonic flight. For orientation, the generic flow pattern we study here is illustrated in Fig. 1.

Observationally, wind-jet combinations are found within protostellar cores (T. A. Movsessian et al. 2007) and active galaxies (S. Silpa et al. 2021). Their interaction may help explain some properties of blue-shifted cold gas and shell excitation (M. Krause & M. Camenzind 2004; T. Oosterloo et al. 2025) with a galactic

flow present before the jet drives through (L. Binette et al. 2000). However, we are motivated here to search for direct dynamical signatures.

A variety of methods have been applied to study dual co-axial jet flows and dual winds. Since the experiments of J. Buckley (1975), it has been recognized that, under a limited range of conditions, the location of the Mach disc in the overpressured axial jet is not sensitive to the speed of the outer flow. This is contradicted by later results as summarized by K.-H. Lee et al. (2004). An important general result is that a co-axial wind reduces the jet exhaust noise. For example, in the work of D. S. Dosanjh, J. C. Yu & A. N. Abdelhamid (1971), the primary jet typically operated at a design Mach number of 1.5, with primary-to-annular overpressure ratios of approximately 4.7. We are thus motivated to ask if the jet noise we found under general supersonic conditions of M. D. Smith & C. Richards (2023) will persist or be suppressed by an encompassing wind.

Here, we perform a systematic study although we still have to restrict the analysis. In terms of physics, we assume adiabatic inviscid hydrodynamics. In terms of jet dynamics, we take a jet flow from a circular nozzle. For the wind, we take an unbounded atmosphere flowing past and being defined on the plane containing the nozzle. Both jet and wind enter parallel to the symmetry axis.

The relatively high pressure of the exhausting gas from the nozzle causes the jet to expand, resulting in a diverging channel. Being supersonic, the pressure on the axis does not immediately fall. However, once the pressure at the channel boundary has

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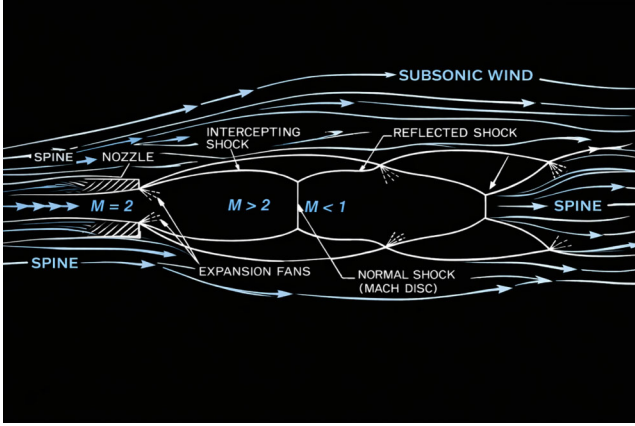


Figure 1. Sketch of the flow pattern of a subsonic wind flowing past an underexpanded jet including some common terminology used to describe the flow pattern when Mach discs are present. The radius of a Mach disc is denoted as height. Here, we are studying a cross-sectional profile and the triple point is actually a circle. Taken and heavily modified from T. Adamson & J. A. Nicholls (1959).

reached the ambient value, the axial pressure has overcompensated and is now underpressured. Therefore, the jet now reacts by converging and the channel narrows (e.g. R. Courant & K. O. Friedrichs 1948).

If the jet overpressure is mild, oblique shocks are sufficient to mediate the converging jet. The channel is slender and pressure jumps are small. In this case, a repeating conical shock pattern is generated that appears as a series of diamond-shaped pressure enhancements along the axis (e.g. E. Franquet et al. 2015; M. D. Smith & T. L. R. Keogh 2022).

For high overpressures, the initial large divergence and following convergence cannot be mediated near the axis by oblique shocks alone. A Mach shock disc then intercepts the jet spine, connected to incident and reflected shocks at the circumference of the disc, as sketched in Fig. 1.

Thus, the two classic flow patterns of shock diamonds and Mach shock discs are set up for low and high overpressures, respectively. The precise pattern depends on a critical overpressure depending on factors such as the overpressure and Mach number (M. D. Smith & C. Richards 2023), as well as the specific heat ratio and opening angle of the nozzle (M. D. Smith et al. 2025). At high Mach numbers, we found the critical overpressure to be $\kappa_{crit} \sim 0.44M_{jet}^2$ where M_{jet} is the jet Mach number at the nozzle (M. D. Smith & C. Richards 2023), with hybrid patterns and variations near the critical value.

In the absence of a wind, oscillations are inherent in the shock configurations due to a feedback loop in which the external medium is involved (C. K. W. Tam 1995). The oscillatory cycle begins with the stand-off shock moving downstream, disturbing the adjacent ambient medium. The ambient medium then transmits a sound wave upstream which raises the pressure and, in so doing, reduces the overpressure. However, in reducing the overpressure, the stand-off shock shrinks back towards the nozzle (M. D. Smith & T. L. R. Keogh (2022)). Once the sound wave has weakened, the jet stand-off shock moves out again. The non-linear nature of the wave motions and the back-flow of waves emanating from subsequent shocks or from the turbulent plume leads to the more random screeching noise of exhausts. This

study took a jet flow from a hole in a wall and will be advanced here by replacing the wall with a wind.

Under what astrophysical conditions will a jet that is overpressured be relevant? Planetary and cometary fissures release supersonic jets from a sub-surface reservoir. However, in galactic and stellar environments, we require the jet to propagate through large pressure drops over small distances in order for a nozzle flow to be applicable.

A potential example is the Hercules A radio galaxy in which a confined jet suddenly exits into a medium where it becomes highly overpressured (D. L. Meier, A. C. Sadun & K. R. Lind 1991). Such a configuration could arise when a jet exits from a galactic core into a circum-galactic medium or from a protostellar core into a molecular cloud. The gravitationally confined core is then separated from the unbound surroundings at the Bondi radius (H. Bondi 1952; R. Edgar 2004). The jet is then subject to a sudden external pressure fall as it then enters a uniform medium.

There are two essential questions to be answered here. First, can a slow wind alter the flow pattern? Secondly, can the power transmitted into the ambient medium be suppressed? Resolving these issues can have broader consequences. If a wind encompasses the jet, one could expect the oscillatory motions, which lead to the propagation of exhaust noise in general, to be suppressed. This may prove to be important in astrophysics since these compression waves could be responsible for, or at least contribute to, both support against inflow of gas in galactic haloes and protostellar cores, as well as inducing acceleration of star formation, and recycling metal-rich gas into the distant surroundings. While we found the latter to be important under constant jet conditions (M. D. Smith & C. Richards 2023), with the addition of pulses into the overpressured jet leads to the propagation of compression waves into the surroundings which take the form of coherent ripples (C. Richards & M. D. Smith 2024).

From the observational perspective, there is evidence for co-axial flows with fast spines and slow sheaths (F. Marin et al. 2024). Here, a jet spine is the primary axial flow while a sheath is the flow within a surrounding annulus. Disc winds are indeed found to co-exist with jets in a variety of phenomena (A. R. Rodríguez-Kamenetzky et al. 2022; S. Gavino et al. 2024; T. Kayanoki, J. Mao & Y. Fukazawa 2024; J. A. López-Vázquez et al. 2024; D. Rogantini et al. 2025). In one case, it was suggested that an overpressured shocked jet expands laterally and excites/ionizes the wind (N. Roy et al. 2024).

One may thus expect jets not to propagate naked through the ambient medium or to be clothed in a self-produced cocoon, but to be sweeping through a wind. The wind is likely to be relatively slow, dense and cool, and may be magnetically driven. Hence, we are going to make the most basic study here in order to gain insight before later exploring more complex situations. We are thus motivated to find potential signatures which would identify the existence of the wind. We also wish to gain insight into the transmission of energy and propagation of noise when the jet is wrapped within a wind.

2 METHOD

2.1 Problem set-up

For the jet, we take a uniform parallel flow out of a circular nozzle into a vast gas reservoir, which provided the basis for our first computational study (M. D. Smith & T. L. R. Keogh 2022). Both media are ideal adiabatic gasses. The jet drills through the envi-

Table 1. The parameters defining the jet and wind.

Parameter	Pressure	Density	Specific haet ratio	Sound speed	Velocity	Mach number
Wind	p_{wind}	ρ_{wind}	γ	c_{wind}	v_{wind}	$M_{\text{wind}} = v_{\text{wind}}/c_{\text{wind}}$
Jet	p_{jet}	ρ_{jet}	γ	c_{jet}	v_{jet}	$M_{\text{jet}} = v_{\text{jet}}/c_{\text{jet}}$
Wind value	0.6	1	5/3	1	v_{wind}	$M_{\text{wind}} = v_{\text{wind}}$
Jet. value	0.6κ	η	5/3	$\sqrt{\kappa/\eta}$	v_{jet}	$M_{\text{jet}} = \sqrt{\kappa/\eta} v_{\text{jet}}$

ronment leaving behind the exhaust, the field near the nozzle, which settles down to reach a final flow structure. The type of flow and shock pattern was then elucidated by also varying the Mach number, up to Mach 8 (F. Duronio, C. Villante & A. De Vita 2023; M. D. Smith & C. Richards 2023).

At the onset of the simulation, a slow subsonic wind blows across the grid with uniform density, pressure and speed in the axial direction. The wind initially occupies the entire computational domain. The wind continues with these parameters to blow by setting the boundary condition at the plane where the jet enters. Thus, a wind parallel to the jet is implemented over the entire plane. The key point is that the jet is overpressured relative to the wind and its immediate expansion creates an obstacle for the wind adjacent to the jet to negotiate.

All media are adiabatic and inviscid hydrodynamics is applied. These are generally well modelled by the finite volume code with the viscous effects confined to a narrow boundary layer across which high velocity gradients lead to numerical dissipation. A thin hot and low-density interface region results.

2.2 Parameter set-up

The time unit, t_u , is defined by the jet nozzle radius R_{jet} and the initial wind sound speed, c_{wind} : $t_u = R_{\text{jet}}/c_{\text{wind}}$. The initial wind pressure is $p_{\text{wind}} = c_{\text{wind}}^2/(\gamma \rho_{\text{wind}})$ where ρ_{wind} is the initial wind density and γ is the fixed specific heat ratio. We generally state parameters in terms of these units with $\gamma = 5/3$ corresponding to a monatomic gas. We normalize lengths to the jet radius $R_{\text{jet}} = 1$. By fixing the initial ambient wind sound speed also to one, the unit of time reduces to $t_u = 1$.

The parameters are summarised in Table 1. The equivalent parameters for the jet at the nozzle are as follows: $p_{\text{jet}} = \kappa p_{\text{wind}}$ and $\rho_{\text{jet}} = \eta \rho_{\text{wind}}$. Thus, the jet sound speed squared is given by $c_{\text{jet}}^2 = (\kappa/\eta)c_{\text{wind}}^2$.

The initial condition includes a significant time, $10t_u$, in which the velocity is ramped up linearly to the final value, v_{jet} . The Mach number is therefore $M_{\text{jet}} = v_{\text{jet}}/c_{\text{jet}}$.

The wind is initially set up with an axial speed of v_{wind} and Mach number $M_{\text{wind}} = v_{\text{wind}}/c_{\text{wind}}$ and is maintained by inflow at the plane containing the jet nozzle for all radii exceeding R_{jet} .

Values of κ and η explored here are chosen in order to facilitate a direct comparison to the earlier wall nozzle study. Hence we have chosen values of $\kappa = 2$ and $\kappa = 8$, with $\eta = 0.1$ to analyse those found to generate different fundamental flow patterns of shock diamonds and Mach shock discs, respectively. We have also investigated both heavy jets, $\eta = 10$, and very light jets, $\eta = 0.01$, finding no trends of significance relative to the $\eta = 0.1$ case study.

2.3 Computational set-up

The astrophysics code *PLUTO*, incorporating Godunov-type shock-capturing schemes, was applied to the problem. It is freely-

distributed (A. Mignone et al. 2007).¹ Having experimented with solvers and resolutions in previous papers in this series, we chose a fast linear interpolation time-stepping Riemann solver with an improved Advection Upstream Splitting Method (AUSM +) as developed by M.-S. Liou (1996) that was found to cope best with pressure issues at the nozzle lip at the highest Mach numbers. This is due to extreme velocity shear across a zone at the wall that can result in negative pressures at a single wall zone. Although not catastrophic, suitable choice of solver avoids this issue. Subsequent comparison of simulations performed with alternative solvers have ensured consistency.

We allow each simulation to evolve well beyond the time for the flow pattern to fully settle down in the near-field region. The near-field of a jet is defined as the region close to the nozzle exit where the flow is still strongly influenced by the initial pressure mismatch as well as the nozzle geometry. Although an exiting jet is subject to surface instabilities, linear wave features will be advected out of the near-field before becoming prominent. On the other hand, the far-field is the developed flow which may consist of a turbulent plume or a collimated jet. Nevertheless, a steady pattern is rarely achieved due to a combination of oscillations, surface waves and turbulence.

The final near-field pattern is found by evolving the flow over long time-scales and taking an atmosphere of sufficient dimensions to ensure that pressure waves can propagate or dissipate freely without regard to a boundary. This is then effectively an infinite reservoir as seen by the jet. The transient waves are usually dispersed by $100t_u$, but we allow all runs to go to $200t_u$ and consider oscillations over the final $10t_u$ to estimate the unsteady nature of the final states. In addition, we produce space-time diagrams and movies to confirm the results.

We present here exclusively two-dimensional simulations with our main analysis limited to the region near the nozzle. This is not a constraining factor provided perturbations to the cylindrical symmetry are not significant in this region before being advected downstream. This has been checked with exploratory three-dimensional runs to be presented elsewhere. We will show that a perturbed circular nozzle leads to distorted shock diamonds and asymmetrically warped Mach discs. Surface wave features attributable to Kelvin-Helmholtz waves are rife at the jet-ambient interface but do not alter the fundamental structure in the near-field region.

The wind is directed parallel to the jet axis and is present in the environment before the jet is initiated at time $t = 0$. Hence, it can be described as co-axial but occupies the entire simulation domain, with a uniform initial entry speed in the z -direction. It is maintained from the boundary at $z = 0$ with the jet replacing the wind for $R \leq R_{\text{jet}}$ and $t > 0$.

Boundary conditions in the cylindrical coordinates (r, z) are as follows. Reflection at $z = 0$ is imposed at the wall, outside of the

¹<http://plutocode.ph.unito.it/>

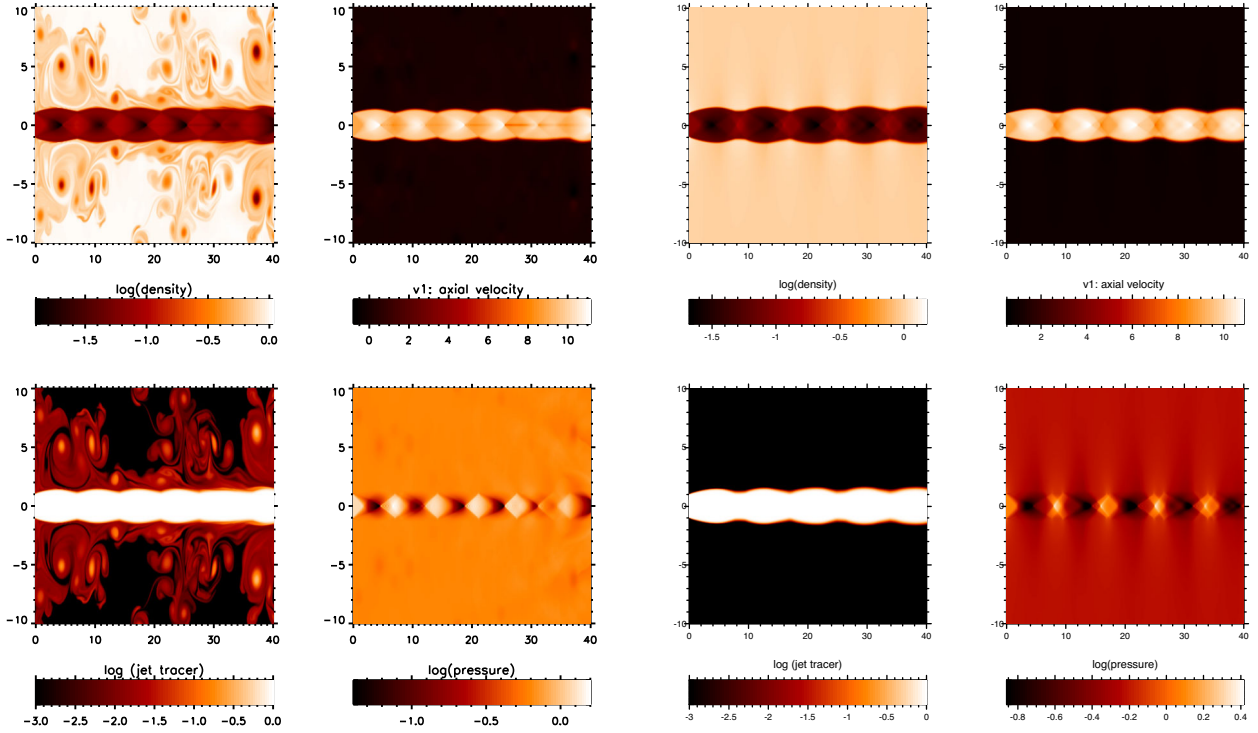


Figure 2. Final crosscut snapshots of the physical parameters for the two extreme cases discussed: wind Mach numbers of $M_{\text{wind}} = 0$ (left panels) and $M_{\text{wind}} = 0.9$ (right panels). The same low jet overpressure of $\kappa = 2$, jet Mach number $M_{\text{jet}} = 2$, and density ratio $\eta = 0.1$ are taken. The time $t = 200$ corresponds to the end of the run. The length-scale is in units of the jet radius. Upper-left sub-panel: density, upper-right sub-panel: axial velocity component; lower-left sub-panel: tracer for jet gas; lower-right sub-panel: pressure. The log(jet tracer) is mass weighted with a minimum set to -3 . Note the reduced axial scaling used in all diagrams to both emphasize structure and compact display convenience.

hole from which the jet enters. Reflection is also implemented at $r = 0$ on the Z -axis to ensure axial symmetry. At the outer edges, we take a free outflow condition. We have found that this is generally not adequate in the long term since the ambient pressure can build up uniformly to any level. Hence, we extend the surroundings to such a degree that the original far-field material remains pristine. Without this outer gas reservoir, the outflow can gradually increase the atmospheric pressure over the long duration of the simulations due to the nature of the outflow boundary condition (e.g. M. D. Smith et al. 2025). In practice, this free outflow condition does not necessarily relieve a pressure rise in the reservoir if there is insufficient pressure gradients to push out the gas. A large reservoir serves as space in which pressure gradients are effective.

The inner uniform cylindrical grids consist of 200 radially distributed zones and 800 axial zones. This converts into $10 R_{\text{jet}}$ and $40 \times R_{\text{jet}}$, respectively, with 20 zones spanning the nozzle radius. A much larger region of staggered zones consists of 100 radially distributed zones and 200 axial zones. This converts into $60 R_{\text{jet}}$ and $140 R_{\text{jet}}$, respectively.

Underlying 1000-frame movies of density and pressure simulations are available in the Zenodo repository, at <https://zenodo.org/uploads/17701974>.

3 RESULTS: LOW-DENSITY JETS OVERVIEW

3.1 Low overpressured jets

A chain of diamond-shaped knots of enhanced pressure are established when a jet is introduced from a circular hole in a wall

with a low ratio of overpressure to Mach number (M. D. Smith & T. L. R. Keogh 2022). This flow pattern approaches a stationary configuration in the near-field of the nozzle, termed regular reflection. We explicitly explore this case with the jet pressure double that of the ambient medium, $\kappa = 2$, density ratio $\eta = 0.1$ and Mach numbers $M_{\text{jet}} = 1.5, 2, 3$, and 4.

Exclusively subsonic wind Mach numbers are explored here. The two extremes in wind Mach numbers approached in this study are displayed in Fig. 2 for a jet Mach number of 2. These display cross-cuts of the physical parameters at the end of the runs.

First note that the vortices in the ambient medium, created in the initial jet advancement, are prominent in the density and tracer panels in the absence of a wind. However, the vortices have been completely removed by the fast subsonic wind. This is consistent with the minimum axial velocity which shows a significant difference on the scale bars shown (top right sub-panels). Thus, without a wind, the swirling vortices which have remained from the initial jet advance provide a negative velocity. When a wind is present, only positive speeds remain.

Note also the input speed is given by $v_{\text{jet}} = M_{\text{jet}} \times c_{\text{jet}} = M_{\text{jet}} \sqrt{\kappa/\eta} = 8.944$, which approaches a maximum close to 11.8 in the subsequent expansion as energy is converted from enthalpy to kinetic. This is slightly exceeded in the absence of a wind.

The second major difference is the separation of the diamond knots (lower-right sub-panels). At the zero wind speed of $M_{\text{wind}} = 0$, the diamonds are separated by ~ 7.5 , while the separation is ~ 9.0 for $M_{\text{wind}} = 0.9$. The increased separation is due to the wind flow around the diverging sections.

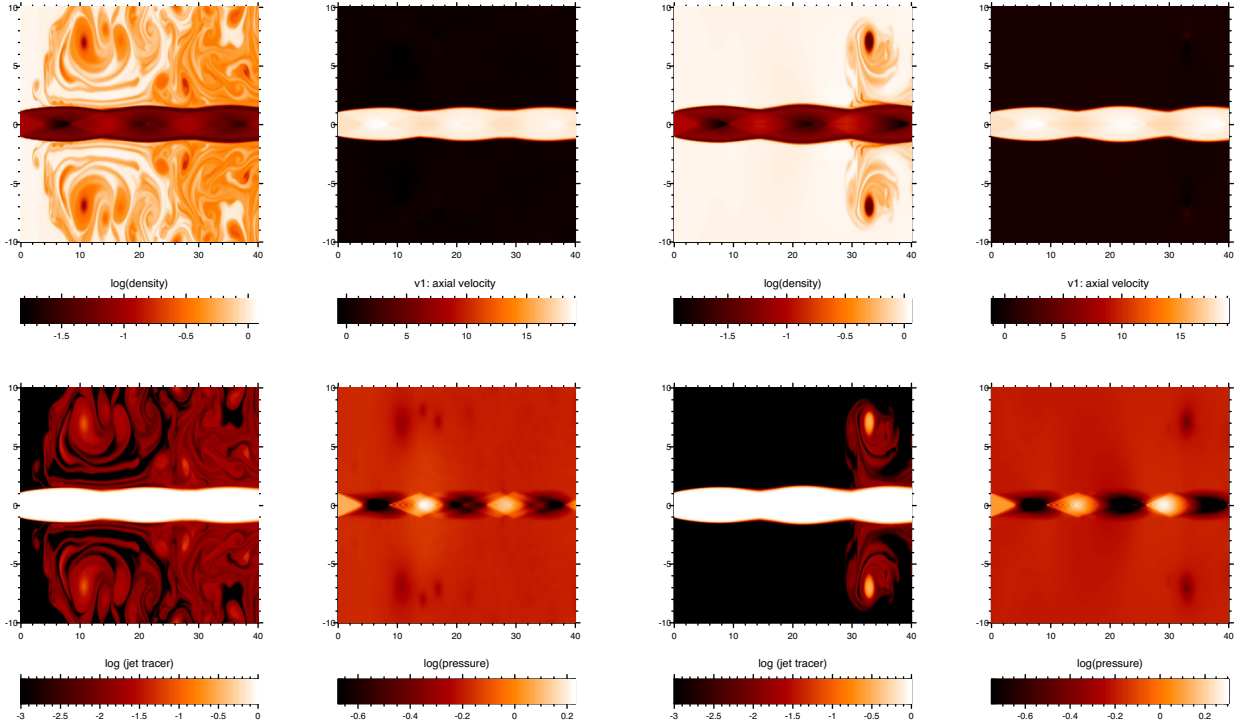


Figure 3. Final crosscut snapshots of the physical parameters for wind Mach numbers of $M_{\text{wind}} = 0.1$ (left panel) and $M_{\text{wind}} = 0.3$ (right panel). A low overpressure of $\kappa = 2$, jet Mach number $M_{\text{jet}} = 4$ and density ratio $\eta = 0.1$ are taken. The time $t = 200$ corresponds to the end of the run. The length-scale is in units of the jet radius. Upper-left sub-panels: density; upper-right sub-panel: axial velocity component; lower-left: tracer for jet gas; lower-right: pressure. Note the axial scaling used in all diagrams to both emphasize structure and display convenience.

As the wind subsequently converges towards the knots, the knots are compressed and reach higher pressures. Moreover, the diamond pressure pattern is now dominated by a distinct compact central zone. For the zero wind, the diamonds show no fine-scale structure while a small crossing shock pattern dominates the internal structure of the diamonds for the high speed wind.

Finally, the fast wind has fully evacuated the vortices which had been produced and sustained from the original cocoon of jet material that in the initial jet advance and, later, within a back-flow. Without the wind, the vortices are maintained and generate an extra pressure on the jet. This additional pressure reduces the mean overpressure of the jet. This is responsible for the shorter separations which were found to be roughly proportional to the overpressure κ in our first study (M. D. Smith & T. L. R. Keogh 2022).

To measure how fast the vortices are cleared, we show in Fig. 3 the equivalent states for $M_{\text{wind}} = 0.1$ and $M_{\text{wind}} = 0.3$ for a $M_{\text{jet}} = 4$. Remarkably, the density and tracer panels show that the lower wind speed has managed to evacuate a narrow region of $\sim 3R_{\text{jet}}$ while the higher speed $M_{\text{wind}} = 0.3$ has cleared all the cocoon structure out to $\sim 30R_{\text{jet}}$. Hence, the wind has been able to advance in the time $200t_u$ at a speed of $0.15c_{\text{wind}}$. Although complex, to account for both results, this suggests an advance speed of $\sim 0.6(M_{\text{wind}} - 0.07)$ that suggests a back flow speed of $\sim 0.07c_{\text{wind}}$.

Space-time diagrams corresponding to the two extreme runs shown in Fig. 2 are provided in Fig. 4. In these diagrams of the evolving axial pressure, the lower-right triangles correspond to the undisturbed wind ahead of the bow shock while the locations of the shock diamonds evolve into vertical bars. The left panel shows that some oscillations in the separations remain through-

out, consistent with the effect of the presence of the vortices. However, if the wind is strong (right panel), the ambient medium is uniform and all oscillations are suppressed.

How the slow wind drives out the cocoon and fully stabilizes the jet is best seen in the movies on the Zenodo repository. It is illustrated here using three frames of the density at times $50t_u$, $120t_u$, and $190t_u$ in Fig. 5. At first, the cocoon is fully established. Once the jet has advanced, the wind gradually pushes on the cocoon, taking over and slowly setting all the vortices in motion downstream.

3.2 High overpressured jets

When the jet enters with a high overpressure, a Mach shock disc is required to mediate between the oblique incident and reflected shocks. The shock fronts meet at a triple point in the planar case, or triple ring for a cylindrical jet.

We find that a new flow pattern arises when a subsonic wind is present around a high-pressure jet. In the absence of a wind, the stand-off shock is a Mach disc which is followed downstream by a turbulent plume as shown in Fig. 6 (left panels). The Mach shock disc is subject to large oscillations as exhibited through the corresponding space-time diagram (the left panel of Fig. 7).

In contrast, when the wind sweeps the medium clean of the deposited jet gas from the initial advance and back-flowing cocoon, the jet becomes well collimated and ordered. The plume is replaced by a series of Mach shock discs. This is illustrated in the right panels of Fig. 6 for a wind speed of $M_{\text{wind}} = 0.5$. The chosen wind speed has no bearing on the final pattern at $t_u = 200$ being steady once the wind has crossed the region.

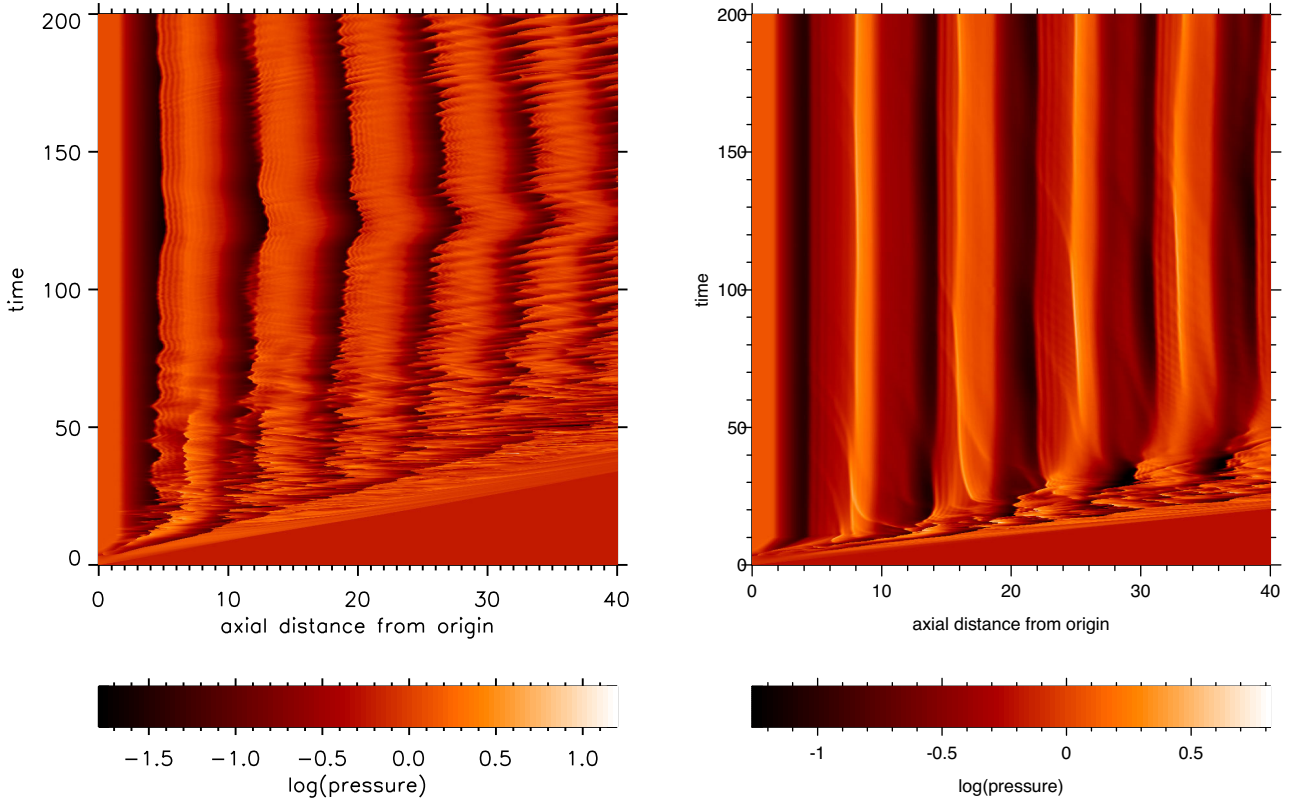


Figure 4. Space-time diagrams for wind Mach numbers of $M_{\text{wind}} = 0$ (left panel) and $M_{\text{wind}} = 0.9$ (right panel). These display the distribution of the pressure along the jet axis as a function of the time for an overpressure $\kappa = 2$, density ratio $\eta = 0.1$, and $M_{\text{jet}} = 2$. Length-scale is in units of the jet radius.

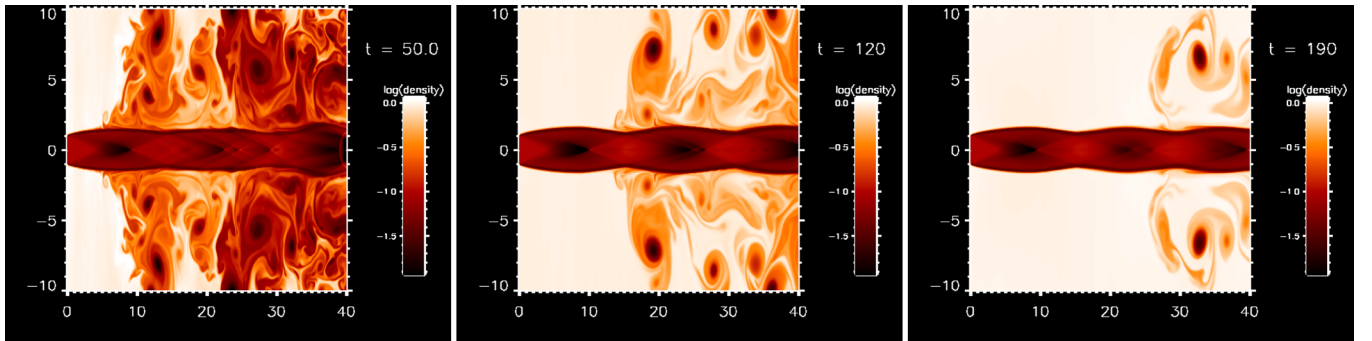


Figure 5. Wind-cocoon evolution shown for the density cross-cuts at three times $50t_u$, $120t_u$ and $190t_u$ of the $M_{\text{jet}} = 4$, $\kappa = 2$ run with a wind speed of $v_{\text{wind}} = M_{\text{wind}} = 0.3$. Note the maximum and minimum displayed densities were normalized to aid comparison. Axes are in distance units of jet radii.

Note that the ambient wind has returned to its original uniform state. In addition, the turbulent plume is constrained into a spine-sheath channel with a prominent fast and dense sheath. After the first strong shock has raised the spine pressure, the following Mach discs are weak, essentially sufficient to hold the pressure to the uniform external wind.

The wind also suppresses pressure feedback and the oscillations in the location of the stand-off distance are absent. The right panel of Fig. 7 shows that the subsonic wind stabilizes the jet pattern after the initial impact in $40 t_u$. Since the wind is relatively dense, it blows the gas away at roughly its wind speed. In the example, the wind speed is $0.5 (\times c_{\text{amb}})$ and so can be seen to even out the entire displayed jet in just over $80 t_u$.

The jet-wind interaction is analysed by studying radial profiles of the physical parameters at the nozzle (left panel) and at a distance of $10R_{\text{jet}}$ downstream (right panel), as displayed in Fig. 8. The profiles are presented for the final time of $t_u = 200$ and the jet and wind Mach numbers are $M_{\text{jet}} = 2$ and $M_{\text{wind}} = 0.5$. Note the wind speed of $0.5c_{\text{wind}}$ is reduced adjacent to the nozzle as the expanding jet protrudes into the wind (blue dashed line) while the density is significantly increased (black dotted). Downstream (right panel), the pressure and density have fallen to low values. The radial velocity profile displays a converging sheath (red dot-dashed line) outside of the expanding sheath. Overall, the profiles at this late time confirms that a steady flow is achieved with only a small perturbation to the wind.

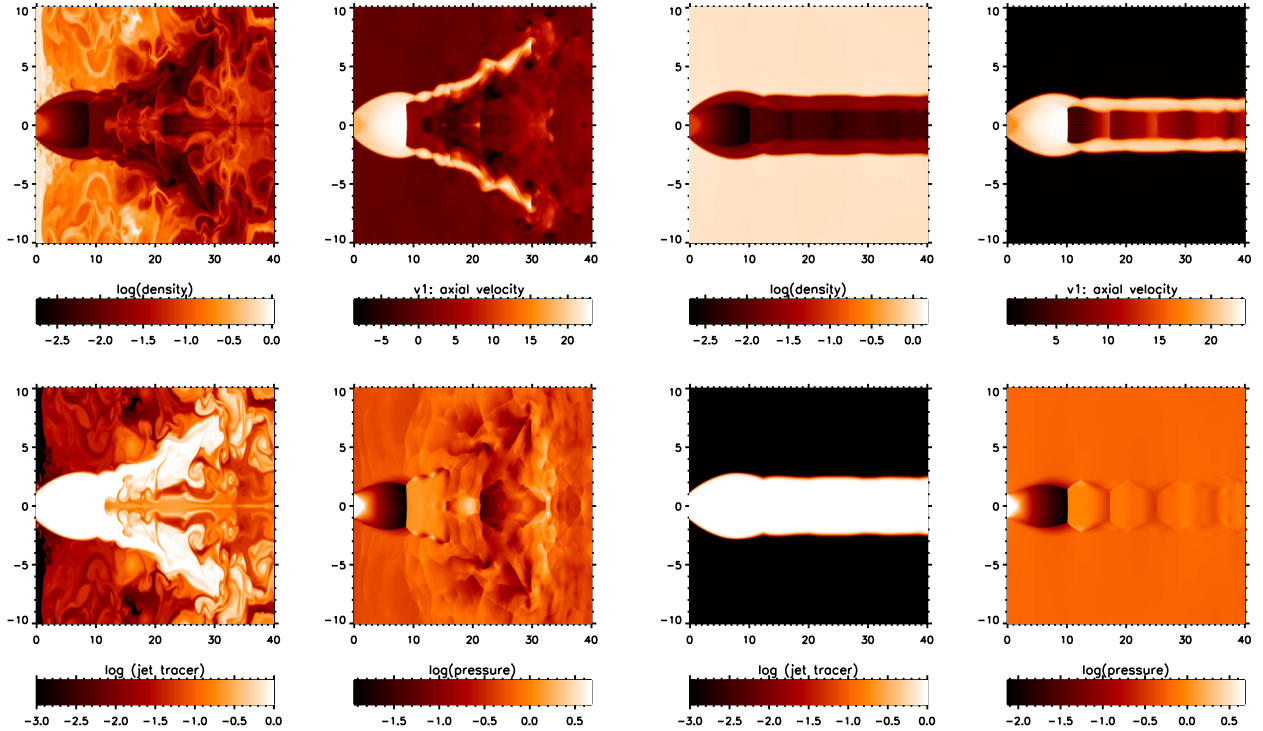


Figure 6. High overpressure comparison for wind Mach numbers of $M_{\text{wind}} = 0$ (left sub-panels) and $M_{\text{wind}} = 0.5$ (right sub-panels). The distributions of physical parameters for a jet with $M_{\text{jet}} = 2$, overpressure $\kappa = 8$ and density ratio $\eta = 0.1$. The time $t = 200$ corresponds to the end of the run. The length-scale is in units of the jet radius. Upper-left panel: density; upper-right panel: axial velocity component; lower-left panel: tracer for jet gas; lower-right panel: pressure.

3.3 Jet Mach number

The jet Mach number and overpressure together determine the flow pattern as found in the context of jet flows from wall nozzles. With the inclusion of the subsonic wind, however, we find that the jet remains collimated rather than degenerating into a turbulent plume. Remarkably, the jet now contains a series of Mach discs. We can show that the spacing between the Mach shock discs increases with the jet Mach number, as indicated in the four pressure cross-sections of Fig. 9. In all cases, the spacing of the stand-off shock from the nozzle is larger than that between the following pairs of shock fronts.

4 DISCUSSION

4.1 Jet trends

We have explored the generic problem of co-axial wind-jet interactions in the case of an overpressured jet and a subsonic wind. This may be relevant to outflows from young stars where atomic jets are surrounded by bipolar outflows, as well as to galactic-scale jets where a galactic wind is present. In the case of protostars and young stars, we can envisage a fast jet being launched into a slow molecular wind (e.g. C. J. R. Lynch & M. D. Smith 2020). It is not clear if similar situations arise within galactic nuclei although jet-wind systems have been proposed (Gopal-Krishna, P. J. Wiita & S. Joshi 2007). In addition, models for the release of an overpressured jet and its subsequent recollimation is the theme of many interpretations on both scales. This is further discussed by M. D. Smith et al. (2025) and some potential parameters tabulated by M. D. Smith & T. L. R. Keogh (2022), where such overpressures were proposed to arise at the edges of galactic nuclei or galactic

halos where gravitationally bound and unbound gas meet at the Bondi radius.

A series of uniformly spaced shells within the protostellar jet of IRAS 15398–3359 has been well resolved with *James Webb Space Telescope* by Y. Okoda et al. (2025). A proposed model including simulations of an underexpanded jet was explored by T. Hanawa et al. (2025). These simulations demonstrated that the stand-off Mach disc would be followed by a turbulent plume with a wealth of structure. We remark here that this jet is the most recent one of several outflows, making a surrounding wind to be a distinct possibility. Therefore, the shells may correspond to the immediate post-shock zones of repeated Mach shock discs within an overpressured jet encompassed by an relic outflow. For the protostellar case in general, the wind may correspond to a molecular outflow which is likely to be supersonic. In addition, if driven from an accretion disc, magnetic and centrifugal forces need to be considered. On the other hand, once the jet has penetrated the sub-parsec scale core, a wind may caress the jet leading to the stability properties found here.

In interpreting the jets of radio galaxies, the transport of energy to Fanaroff & Riley FR II radio sources (B. L. Fanaroff & J. M. Riley 1974) takes place with high efficiency. Here, we note that this would be enhanced by the presence of a wind which eliminates oscillations as demonstrated in Fig. 4. We shall show in a follow-up paper that a supersonic wind may go further in this respect by encasing the jet into a well-collimated channel in which shocks are absent.

At high jet overpressures, we have found that a subsonic wind suppresses turbulence but reinforces the shock pattern. This would be a factor which contributes to the prominent jets of Fanaroff & Riley FR I sources. The jets driving these radio galaxies extend to hundreds of kiloparsecs yet retain a bright emission

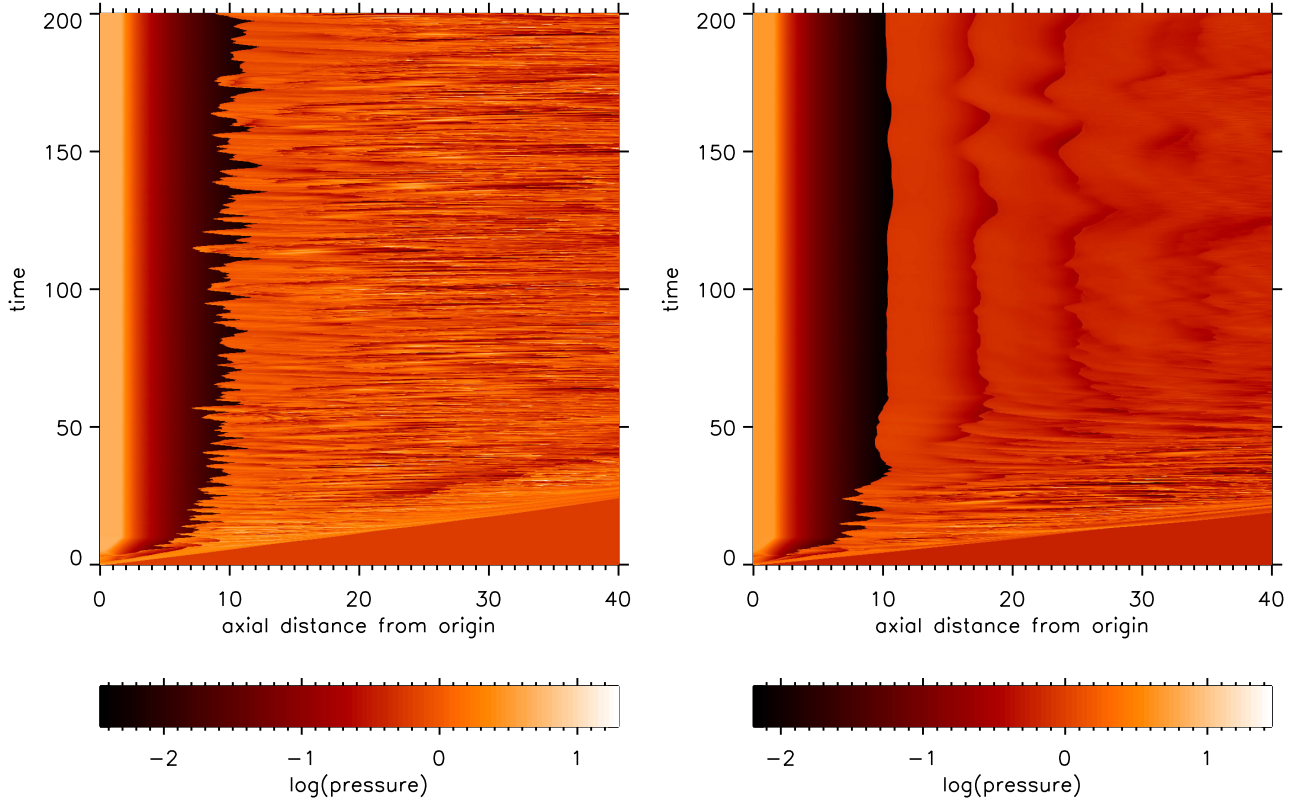


Figure 7. Space–time diagrams for wind Mach numbers of $M_{\text{wind}} = 0$ (left panel) and $M_{\text{wind}} = 0.5$ (right panel). The distribution of the pressure along the jet axis as a function of the time for a jet with $M_{\text{jet}} = 2$, overpressure $\kappa = 8$ and density ratio $\eta = 0.1$. Length-scale is in units of the jet radius.

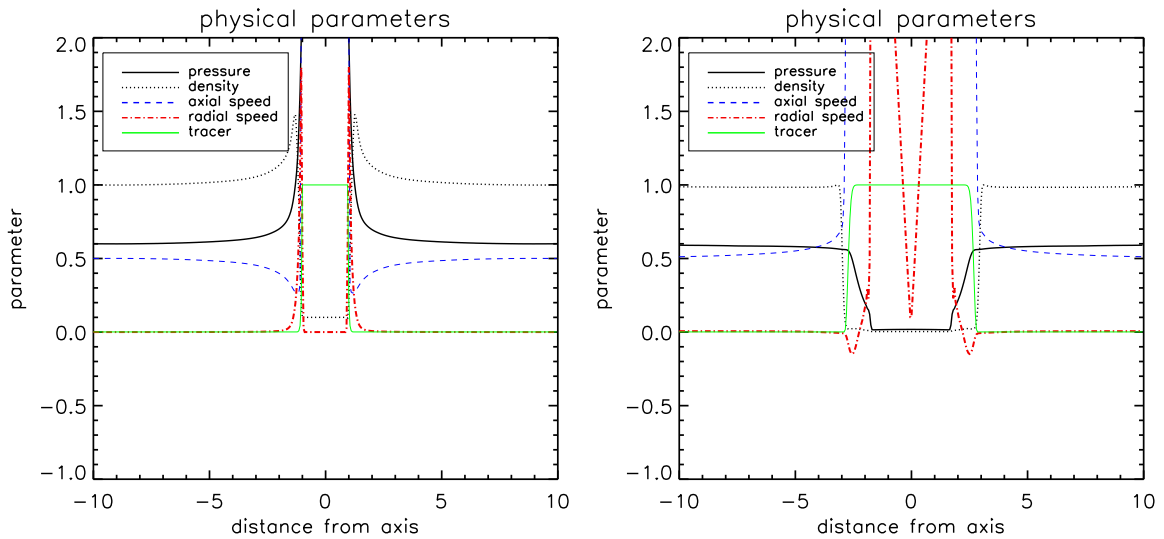


Figure 8. Radial profiles of parameters for a light high overpressured jet taken at the nozzle (left panel) and at an axial distance of $10 R_{\text{jet}}$ from the nozzle (right panel). Physical parameters are shown as a function of the radial distance from the jet axis. A light jet with $M_{\text{jet}} = 2$, overpressure $\kappa = 8$ and density ratio $\eta = 0.1$ is taken. Note that the jet axial speed and pressure are not displayed to their full magnitude in order to highlight the jet–wind interaction.

trail. On the other hand, the absence of a wind would leave the jet prone to oscillations and, at high overpressures, a subsonic plume beyond the stand-off shock. This would be commensurate with the Fanaroff & Riley Class 0 sources which may be associated with disrupted jets (R. D. Baldi, A. Capetti & F. Massaro 2018).

4.2 Energy and environment

It is of interest to study the lateral transport of energy from the jet in order to evaluate noise levels through atmospheres. In astrophysics, this energy flow would contribute to supporting the

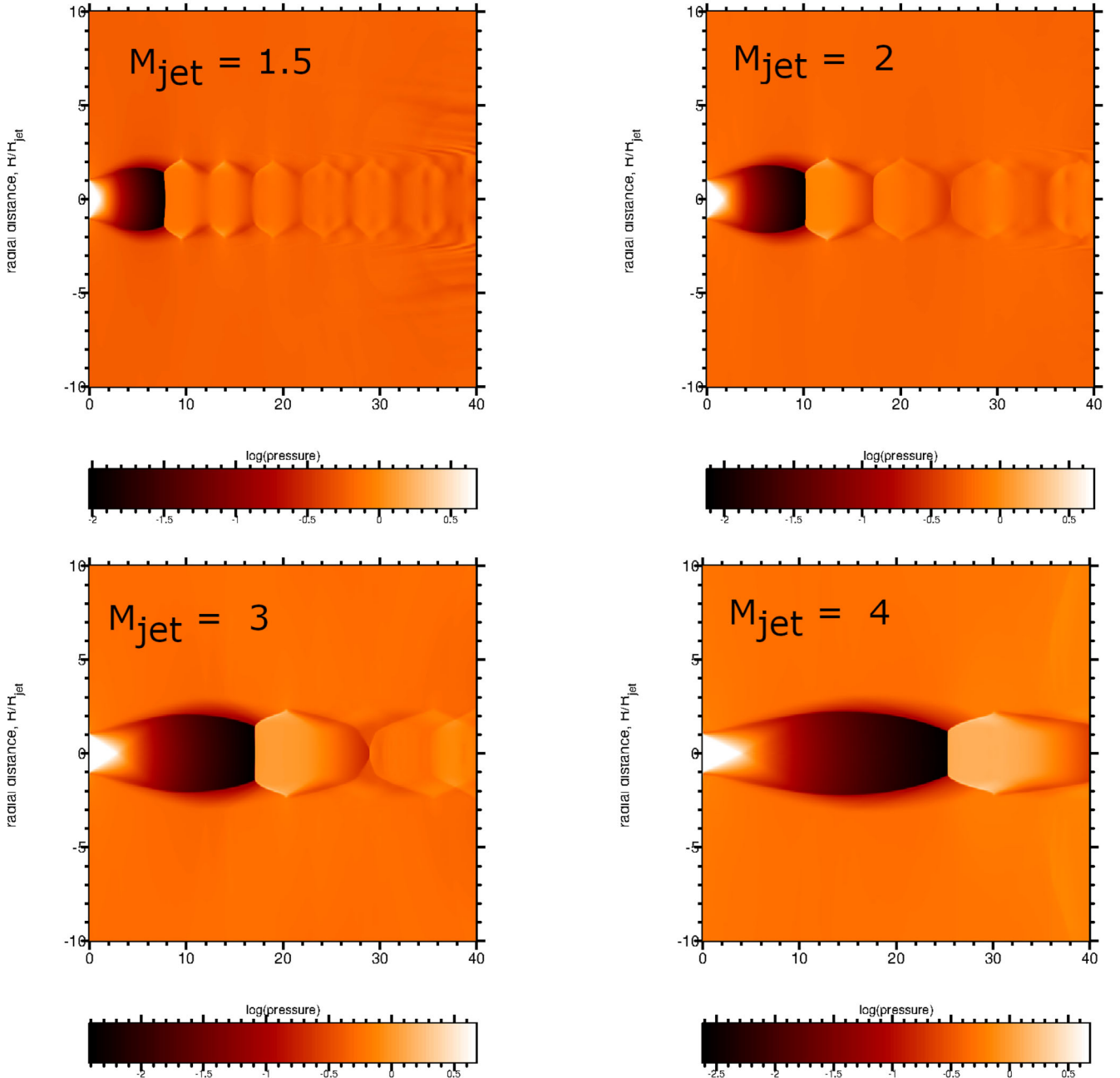


Figure 9. A series of Mach discs are found for high overpressure jets for a range of jet Mach numbers with other parameters fixed. The wind Mach number is $M_{\text{wind}} = 0.5$. The time is at the end of the simulations at $t_0 = 200$ after the surrounding wind has driven out the vortices and plume and the jets are transformed to collimated steady flows. The pressure distributions are displayed for the indicated jet Mach numbers. A light jet with overpressure ratio $\kappa = 8$ and density ratio $\eta = 0.1$ are taken.

ambient medium against cooling, gravitational collapse and star formation. However, jets drill fast and efficiently due to their high momentum flux and so emerge from their cores, depositing most of their resources beyond the core region. Nevertheless, it has been noted that the conversion of a few per cent of directed jet power into the core environment would be sufficient to alter their evolution.

To approach these phenomena, we illustrate for low overpressured jets in Fig. 10 the total fluxes of energy crossing the uniform cylindrical grid for the entire duration of the sim-

ulations. At each time, we sum up for each component of energy the flux through a census cylindrical surface to yield the lateral flux, and through the cylinder's end cap to provide the axial fluxes. The census cylindrical surface is taken to be at 90 per cent of the uniform region. The integrated powers are converted into non-dimensional units as scaled by the unit $\rho_{\text{wind}} c_{\text{wind}}^3 / 2$. Thus, the indicated lateral powers are those through the girth of the cylindrical surface while jet powers are the total fluxes through the caps near the end of the grid.

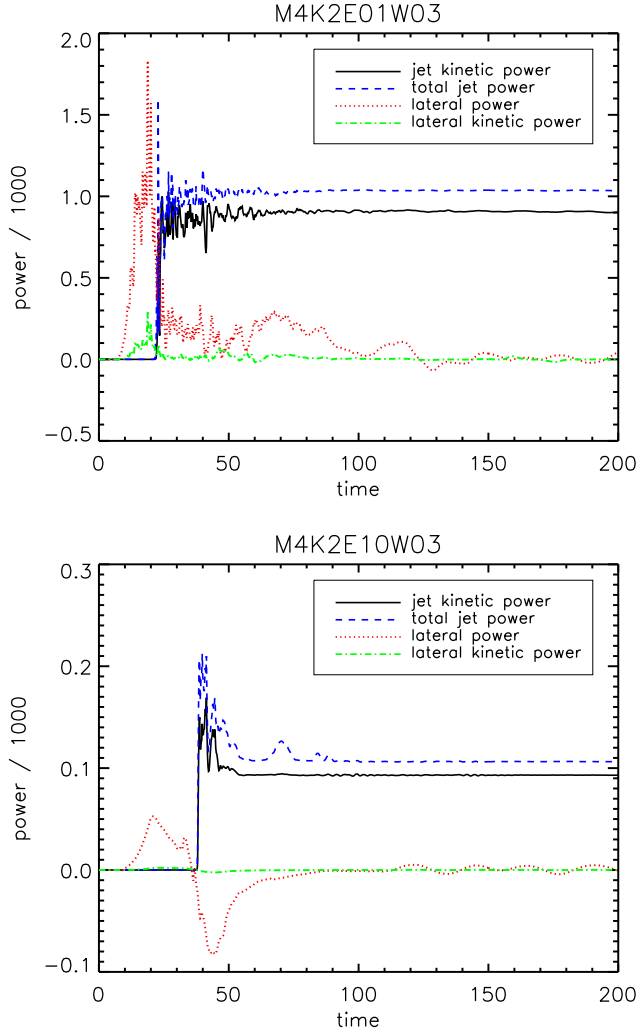


Figure 10. Evolution of the lateral and forward escape of energy for jets encompassed by a subsonic wind. A comparison of relative jet densities, $\eta = 0.1$ (upper panel, light jet) and $\eta = 10$ (lower panel, heavy jet). The jet Mach number is 4, overpressure 2 and wind Mach number is 0.3 for both panels. The indicated energy fluxes are calculated by integrating the passage through a cylindrical sheath and circular cap, drawn with radius 180 zones and axial length 720 zones. Initially, the jet enters the grid and it takes ~ 30 time units to cross to the cylinder cap which is at 90 per cent of the uniform grid length. These are the net power outflows in simulation units.

A wide bow shock leads the initial jet advance which for a short time will markedly disrupt the environment. This impact generates the peaks in power components shown in Figs 10 and 11. The bow first crosses the radial girth at $\sim 20t_u$ (red-dotted lines), and reaches the cap at $\sim 20t_u - 40t_u$ (black-solid and blue-dashed lines). However, once the jet has exited the inner core region, the ambient medium recovers as the pressure within the reservoir pushes back. Nevertheless, in the very long terms considered here some energy is still emitted radially in the absence of a wind as shown by C. K. W. Tam (1995) and M. D. Smith & T. L. R. Keogh (2022). This is due to the jet oscillations caused by the overpressure and the resulting surface motions related to surface waves (non-linear waves moving at the Kelvin–Helmholtz speed).

For the light jet in the upper panel of Fig. 10 the lateral power reaches a peak at $\sim 20t_u$, as shown by the red-dotted line in

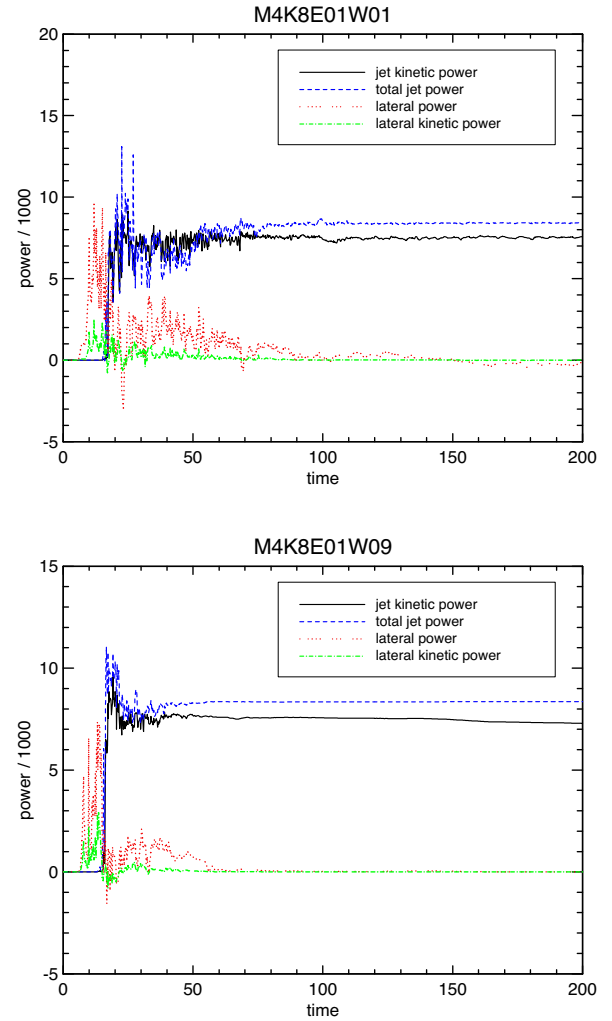


Figure 11. Evolution of the lateral and forward escape of energy for $\kappa = 8$ overpressured jets encompassed by subsonic winds. A comparison of the effect of the wind Mach number with $M_{\text{wind}} = 0.1$ (upper panel) and $M_{\text{wind}} = 0.9$ (lower panel). The jet Mach number is 4, overpressure 8 and density $\eta = 0.1$ for both panels. The indicated energy fluxes are calculated by integrating the passage through a cylindrical sheath and circular cap, drawn with radius 180 zones and axial length 720 zones. Initially, the jet enters the grid and it takes ~ 30 time units to cross to the cylinder cap which is at 90 per cent of the uniform grid length. These are the net power outflows in simulation units.

Fig. 10. Thus, the impact of the jet is first felt on the shaft of the cylinder. Without a wind, a lateral energy flow is sustained at the 5 per cent - 10 per cent level (see fig. 15 of M. D. Smith & C. Richards 2023). However with the wind, the subsequent lateral flow of energy then remains high at 20–30 per cent but only up to a time $\sim 120t_u$. Thereafter, there is no discernible flux.

We thus find that the wind provides a protective coating to the far environment. By quashing the jet oscillations, the jet is effectively silenced. On the other hand, for a long period the wind is clashing with the cocoon, expelling mass and energy until the wind is able to directly blow the cocoon out along the axis. We could have expected that the wind will be continuously deflected by the diverging jet sections. This would then lead to a secondary source of radial outflow. However, we see no evidence for this:

the subsonic wind undulates over both converging and diverging sections without, on average, expelling energy.

For a heavy jet, a large inward lateral energy flow occurs after the initial advance (the depression in the red-dotted line in the lower panel of Fig. 10). Without a wind, a significant circulation pattern is set up in the ambient medium which results in the radial inflow of the wind gas along the cylinder, balanced by mass-loss through the cap (see C. Richards & M. D. Smith (2024)). Here, however, this is only temporary and once the jet channel has reached a steady state, energy and mass is transported via the wind through the cap as illustrated in Fig. 5.

The effect of a subsonic wind on the flow of energy for a high overpressure jet is shown in Fig. 11. We illustrate the difference between a low-speed (upper panel) and high-speed wind (lower panel). The high-speed wind quickly eliminates the turbulent plume, and a very steady axial energy flow ensues. On the other hand, some variation is retained in the axial flow for the low-speed jet. The high-speed wind is also able to eliminate the effect of the turbulent plume on the lateral flow associated with the high overpressure within a short time of $\sim 60t_u$. The low-speed wind acts gradually but still is able to reduce the radial flow $\sim 140t_u$.

4.3 Sweeping of vortices by the wind

The opposite lobes of classical radio galaxies extend back towards the galactic nucleus. In many cases, these back-flowing wakes form an entire bridge such that there is no gap between the double lobes while in other case there is a distinct gap (P. Alexander & J. P. Leahy 1987; R. G. Strom et al. 1990; J. P. Leahy & R. A. Perley 1991) with a sharp inneredge (Gopal-Krishna, et al. 2007).

Our simulations show that debris jet material is deposited and remains adjacent to the jet well after the jet and associated bow shock have advanced far beyond the field close to the nozzle. In the present two-dimensional study, this gas occupies a turbulent cocoon which degenerates into prominent vortices in the form of vortex rings. These are long-lived features and may appear as a wide bridge between the advancing working surface and the jet origin. The debris is well illustrated here in the left panels of Fig. 2 when there is no wind.

A subsonic wind is sufficient to gradually sweep away the vortices. The time taken to achieve this is explored here. Fig. 12 presents the clearing distance as a function of time for three major parameters. For this analysis, we examined the value of the jet tracer at a radial distance of $5R_{\text{jet}}$ above the jet axis. We then applied a maximum tracer value of 0.003 to capture essentially all jet debris. This generates a quite sharp division as confirmed in a space-time diagram for the jet tracer at this radial distance. This is displayed in Fig. 13. Note the lower-right dark areas corresponds to the undisturbed ambient medium while the bright ridge corresponds to the cocoon. One can then see how this cocoon becomes turbulent before breaking up into vortices.

The time taken to clear the debris is not sensitive to the Mach number. This is demonstrated in the top panel of Fig. 12. After a time lag of $\sim 10t_u$, the widening cocoon appears as a spike which rapidly declines as the cocoon spreads laterally. Thereafter, the leftovers of the jet cocoon are swept downstream an approximately linear fashion with time.

The wind speed is the crucial factor as might be expected. The middle panel of Fig. 13 again show mainly linear evolution with some variations as individual vortices become caught in the wind. The clearing speed varies with a value $\varepsilon \sim 0.5 - 0.7$ of the wind

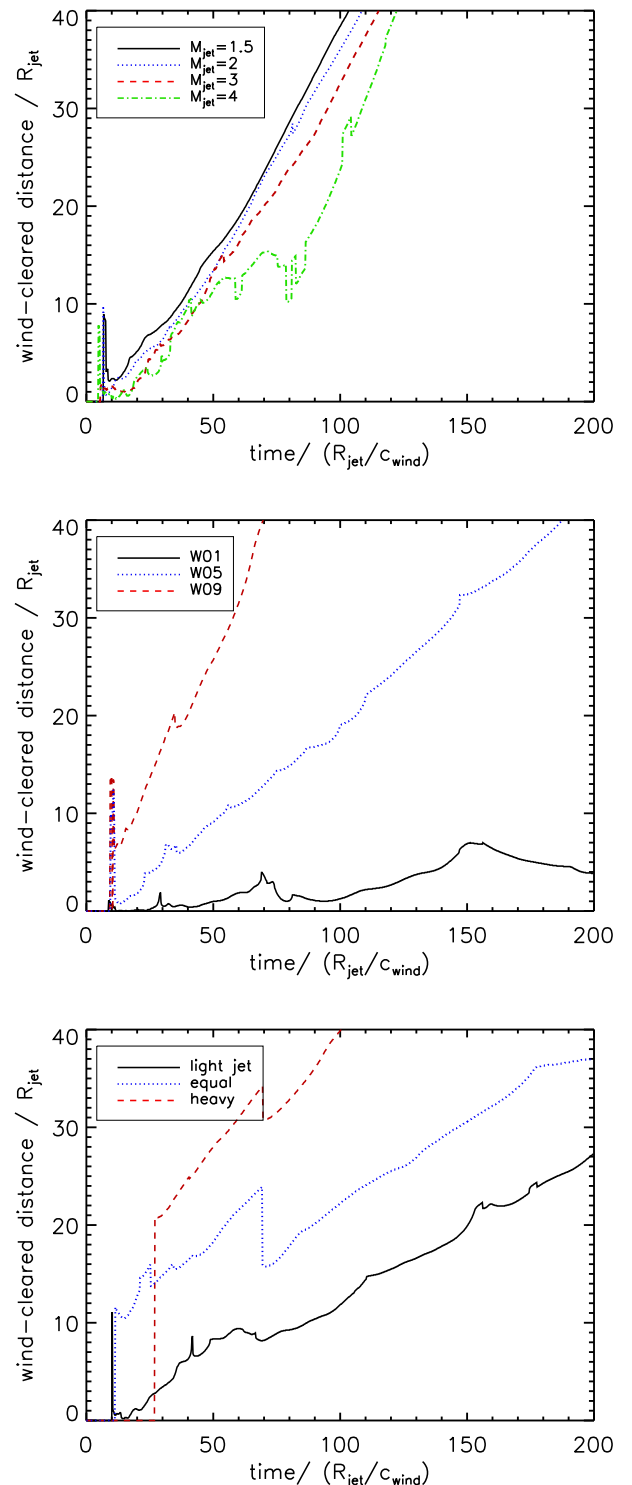


Figure 12. The distance to which vortices surrounding the jet are swept out by the wind as a function of time. In detail, the census is a line drawn at a radius of $5R_{\text{jet}}$ above the jet axis and is taken as the fzone where the jet tracer first exceeds 0.0032 along this line. Top panel: the weak dependence on indicated jet Mach number for a wind speed of $0.5c_{\text{wind}}$, overpressure $\kappa = 8$ and density ratio $\eta = 0.1$. Middle panel: the strong dependence on the wind speed as indicated by the wind Mach number 0.1, 0.5, and 0.9, denoted as W01, W05, and W09, for $M_{\text{jet}} = 4$, $\kappa = 2$, and $\eta = 0.1$. Lower panel: dependence on jet density for a relatively light $\eta = 0.1$, equal $\eta = 1$ and heavy jet $\eta = 10$.

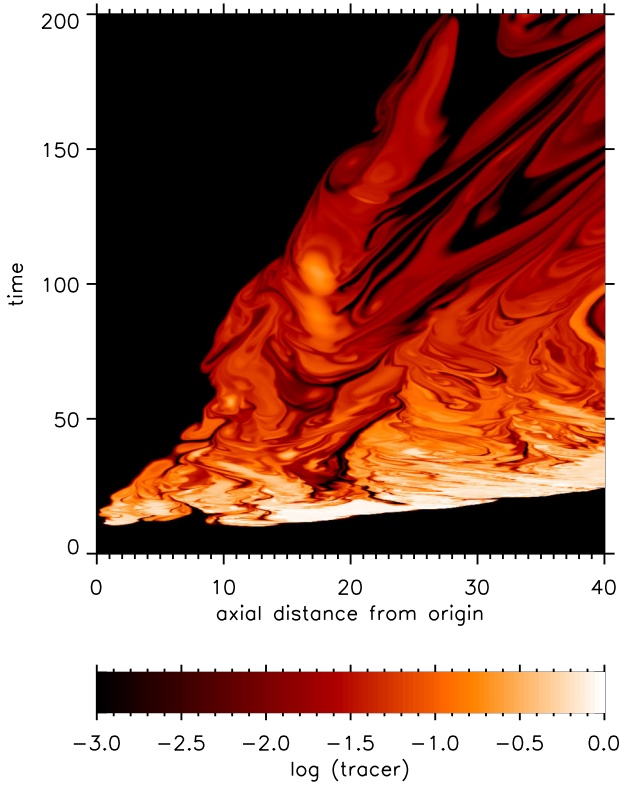


Figure 13. A tracer space-time diagram displaying the magnitude of the jet tracer in the surrounding medium which gradually gets blown away by the subsonic wind. The tracer is evaluated at a distance $5R_{\text{jet}}$ above the jet axis. The jet Mach number is $M_{\text{jet}} = 4$, wind Mach number is $M_{\text{wind}} = 0.3$, with $\kappa = 2$ and $\eta = 0.1$. Tracer values below 0.001 are set to this minimum for display purposes. The lower-right areas represents untouched wind material ahead of the jet while the top left is the section cleared by the wind.

speed. The speed is not only determined by the pressure as the subsonic wind becomes into contact with the debris but also the deflection of the wind radially outwards.

The jet density is a second factor to investigate. Light jets are inefficient at penetrating the ambient medium, and so deposit their energy into a wide back-flowing cocoon. On the other hand, heavy jets eject gas into a narrow cocoon. Since they are heavy, however, they can contribute to the tracer. Thus, the lower panel of Fig. 13 shows that the heavy jet (red dashed line) remains clear of the cocoon gas until the debris has spread radially at $\sim 27t_u$.

5 CONCLUSIONS

What are the signatures that would specifically identify that an overpressured jet is enshrouded by a wind? We have found answers but should note that, to begin, we have input a uniform supersonic jet into a co-axial subsonic wind. We also exclusively analyse hydrodynamic simulations with adiabatic gasses and eject the jet from a circular nozzle. Our interest is in the near-field, studying the emerging shock patterns well after the jet has vacated a channel through the wind. In this near-field to the nozzle, we can discount surface instabilities and employ two-dimensional simulations.

Hence we study the fundamental flow patterns ignoring many physical processes including those due to magnetic fields, relativ-

ity, rotation, chemistry and cooling. This is a follow-up to recent systematic analyses on the effect of overpressure, Mach number, pulsation and opening angle, all of which have a bearing on the flow behaviour (M. D. Smith & T. L. R. Keogh 2022; M. D. Smith & C. Richards 2023; C. Richards & M. D. Smith 2024; M. D. Smith et al. 2025).

We find that the presence of a subsonic wind is sufficient to alter the flow structure. At low overpressures, the wind drives out the cocoon and vortices left behind by the jet. Internal to the jet, at high subsonic speeds, the diamond shock pattern is dominated by a sharp central zone of higher pressure. This is a potential diagnostic for the existence of a wind when the jet emissivity is related to the pressure, as would be expected. In addition, the location of the stand-off shock is moderately increased, a difference that would generally be hard to detect especially due to uncertainties in the projection angle of the jet axis in astrophysical systems.

Jets with high overpressure relative to the wind become well collimated and contain multiple Mach shock discs once the wind has driven out the turbulent plume which formed initially. The discs form in a wide spine while a fast narrow sheath separates the spine from the wind. A multiple Mach disc pattern can also occur in low overpressure jets under certain limited conditions involving a narrow range of wide opening angles [see case (d) of M. D. Smith et al. (2025)].

There are no long-term disturbances to the environment due to the wind-jet interaction. The wind suppresses the oscillatory motions in the overpressured jet, reducing the exhaust noise. It will be of interest to see the noise levels when the wind itself is also supersonic, analogous to supersonic flight.

The subsonic wind would clear a gap between the double lobes of a radio galaxy or a bipolar nebula. In the absence of a wind, remnants of the jet overspill remain in the nozzle near-field as permanent features (see the left panels of Fig. 2). A wind, however, removes these vortices at a rate proportional to the wind speed. For the subsonic case studied here, there is no shock produced in this interaction and so no obvious signature to search for.

We can evaluate the size of the gap in terms of the lobe length. The interface between the wind and lobe overspill advances at $\varepsilon \sim 0.5 - 0.7$ of the wind speed (see Fig. 12). In the meantime, the advance of the jet head (i.e. the working surface) is estimated to be $U \sim \sqrt{\eta}v_{\text{jet}}$ for a light jet (M. D. Smith & T. L. R. Keogh 2022). This is written here as $U \sim \sqrt{\kappa}M_{\text{jet}}$. Hence the region cleared by the wind is a fraction $\varepsilon M_{\text{wind}}/(\sqrt{\kappa}M_{\text{jet}})$ of the total length of the source.

The wind not only generates a gap but also stabilizes the internal jet shock pattern while the jet propagates through the gap. In terms of bipolar lobes, this would reduce the bridge and generate a sharp cut-off. However, given expected high jet Mach numbers, this may be a rare effect. One example is the radio galaxy 3C388 where both the visible jet and lobe gap are at the same distance from the nucleus (J. O. Burns & W. A. Christiansen 1980). As a wind sweeps up and ejects the vortices, an inner edge of accumulated gas and transverse magnetic field results. To observe this effect requires low radio frequency observations at high resolution. The Low-Frequency Array (LOFAR) provides this capability and examples akin to this phenomena are indeed apparent (V. H. Mahatma et al. 2023). New-generation instruments will imminently permit us to investigate whether more sources with the same characteristics exist.

The further potential link to observations is the appearance of a series of Mach shock discs. This implies an inefficient jet with multiple subsonic flow regions interspersed with mildly supersonic regions. As outlined in Section 4, the molecular outflow of IRAS 15398–3359, a Class 0 protostar, can be interpreted in this manner (T. Hanawa et al. 2025). Other differences brought about by the wind are theoretically interesting but observationally small: the disappearance of shock oscillations, a high velocity shear along the boundary with a slow jet spine, and a somewhat higher shock diamond separation.

Will these results extend from the case of a subsonic wind to a supersonic wind? A supersonic wind will not flow smoothly around the diverging jet. Shocks are inevitable as the wind gets deflected. We thus anticipate new observational signatures.

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DATA AVAILABILITY

No new observational data were generated or analysed in support of this research. Simulation source files are available on request. The data underlying this article will be shared on reasonable request to the corresponding author.

Movies compiled from 1000-frame snapshots of a large selection of simulations are available in the Zenodo repository, at <http://zenodo.org/uploads/17701974> or through DOI: 10.5281/zenodo.17701974.

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