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Consideration of gusts, blasts and prolonged velocity bursts in supersonic overpressured jets

Carl Richards¹★ and Michael D. Smith^{1,2}★

¹Centre for Astrophysics & Planetary Science, The University of Kent, Canterbury, Kent CT2 7NH, UK

²Department of Physics, Amrita School of Physical Sciences, Amrita Vishwa Vidyapeetham, Amritapuri Campus, Kollam, Kerala 690525, India

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ABSTRACT

The origin, motion and brightness changes of travelling discrete knots in astrophysical jets remain open to interpretation. Such observations in active galactic nuclei jets have inspired our generic study of velocity bursts propagating along overpressured supersonic jets. As a first step we employ fundamental two-dimensional axisymmetric hydrodynamic simulations. We focus on the region immediately following jet launch in order to understand the basic physics of flow patterns. We systematically explore parameter space for various velocity burst interactions in adiabatic jets, and target jet configurations of interest. A very short-duration burst (*gust*) coherently creates interacting shock patterns as it passes successive recollimation shocks. A longer burst (*blast*) also temporarily reconfigures the channel. Successive shock-shock interactions increase jet pressure, and temporarily establish high pressure concentric reverse cone shells, increase jet diameter, and cause delayed after-shocks. In contrast, a *prolonged-burst* alters jet shape and affects multiple standing-shocks simultaneously. A burst causes a temporary translation of a standing-shock along the jet axis, more so in higher overpressure jets, as well as transmitting a sound wave into the surrounding ambient medium. There is potential to infer some jet physics using observational diagnostics, but more complex simulation physics would be required.

Key words: hydrodynamics – shock-waves – stars: jets – galaxies: jets.

1 INTRODUCTION

Supersonic flows of highly collimated gas emanate from a variety of astrophysical objects such as active galactic nuclei (AGNs), young stars, protostellar cores, some varieties of evolved stars, as well as being released from the surfaces of cometary bodies and solar system moons (M. D. Smith 2012). For AGNs, these jet flows originate from a supermassive black hole (SMBH), which are at the centre of most normal galaxies (J. Kormendy & L. C. Ho 2013), and which are observed on scales up to Mpc (R. Blandford, D. Meier & A. Readhead 2019). They are considered to form when the SMBH spins and the accretion disc is strongly magnetized (R. D. Blandford & R. L. Znajek 1977; J. C. McKinney 2006), and where observations suggest jets are collimated close to the SMBH by magnetic stress (M. Nakamura & K. Asada 2013). Standing knots in AGN jets are stationary emission-bright features and may be considered to be produced by recollimation shocks where the jet flow adjusts to its environment (e.g. O. Hervet et al. 2017). Despite intensive investigation across the entire electromagnetic spectrum, our knowledge of astrophysical jets is still fragmentary and incomplete (G. E. Romero 2021). This applies equally to AGN jets, where there are many open questions, e.g. how are jets launched from near the central super massive black hole (SMBH; R. D. Blandford & D. Payne 1982) and what determines

jet power and its scaling with accretion rate and black-hole spin (R. S. Nemmen et al. 2007)? Concerning jet propagation, how are jets collimated and stabilized over huge length scales (J. C. McKinney & R. D. Blandford 2009), and what is the internal structure of jets (spine–sheath, stratification, velocity fields) (R. Blandford et al. 2019)? Concerning jet luminosity variability, what produces the very rapid variability and extreme flares seen in blazars and some radio galaxies (M. Petropoulou, D. Giannios & L. Sironi 2016)?

Of particular interest are observations of intense compact features which propagate along astrophysical jets (A. P. Marscher & W. K. Gear 1985a; M. Nakamura, D. Garofalo & D. L. Meier 2010; D. Giannios 2013; C. M. Fromm et al. 2016), for example following a central flare. Based upon observations (e.g. M. L. Parker et al. 2016; D. Wilkins et al. 2015), an AGN central flare could be caused by a temporary increase in the SMBH accretion rate. The resulting travelling emission knots are moving disturbances that propagate downstream reflecting variability in the jet flow (e.g. Z. Meliani & O. Hervet 2017a; R. Blandford et al. 2019). However, not all bursts or flares may arise from standing or moving knots, e.g. bright features could also be local interactions with stars or nebulae (B. Snios et al. 2019). Some of the open questions regarding travelling AGN luminosity knots include; What physical processes create the knots e.g. shocks, magnetic reconnection, or some instability (A. Nathanail et al. 2022; E. P. Alves, J. Zrake & F. Fiuza 2018)? How do knots evolve (lifetimes, expansion, cooling, spectral ageing) as they propagate (E. T. Meyer et al. 2013)? What role do

* E-mail: cr704@kent.ac.uk (CR); m.d.smith@kent.ac.uk (MDS)

standing features (e.g. recollimation shocks or nozzle structures) play in producing, rebrightening, or altering travelling knots (O. Hivet et al. 2017)?

Jets are also seen issuing from the young proto-stars in the early phase of low-mass star formation. For stellar jets, observations suggest bright knots are locations of inner recollimation shocks (e.g. M. C. White et al. 2014; T. Hanawa et al. 2025). Many proper motions of jet brightness knots in pro-stellar jets have been observed (e.g. C. Davis et al. 2009; S. Correia et al. 2009; A. C. Raga et al. 2017). Some of them show roughly equal spacings in between knots and bow shocks, suggesting that the knots and bow shocks are produced by quasi-periodical variations in ejections, induced by quasi-periodical perturbations of the accretion in the discs (C.-F. Lee 2020). They can not merely trace quasi-periodical ejections of enhanced jet densities because, alone, they would not produce shocks (A. Frank et al. 2014). There also appears to be examples of quasi-periodical variation in ejection velocities (e.g. J. Santiago-García et al. 2008; M. Reiter & N. Smith 2014), where a shock may be formed as the fast jet material catches up with the slower jet material.

To explain bright moving features in AGN jets (M. L. Lister et al. 2013a), shock wave configurations have been suggested (e.g. A. P. Marscher & W. K. Gear 1985b; G. F. Parascos 2025). Stationary features can trigger brightening of passing knots, redirect trajectories, or accelerate particles (O. Hivet et al. 2017; Z. Meliani & O. Hivet 2017b). The Centaurus A jet shows both fast X-ray knots and possibly stationary radio knots (D. Bogensberger et al. 2024). M. L. Lister et al. (2013b) suggest that in general, high-ejection-rate blazar jets tend to eject features with apparent speeds that cluster about a speed that is characteristic to each individual jet. Some numerical simulations of interacting shocks within AGN jets have been performed, e.g. for low jet/ambient overpressures and short duration bursts (J. L. Gómez et al. 1997). Multiple mechanisms naturally produce localized bright features (J.-M. Martí 2019). Interactions of bursts with standing shocks have also been investigated (e.g. M. H. Cohen et al. 2014). Internal or recollimation shocks may compress plasma and magnetic fields to produce enhanced synchrotron emission (C. M. Fromm et al. 2016; G. F. de Clairfontaine et al. 2021; G. Fichet de Clairfontaine, Z. Meliani & A. Zech 2022).

Inspired by these moving knots in AGN jets, where some classes are sub-relativistic at large scales (R. Laing et al. 1999), we aim to extract their basic properties and eventually relate these to the underlying travelling burst. Here, we focus on physical structures generated by bursts and travelling-shock/standing-shock interactions. This is motivated by noting that essentially observed jets are driven sporadically and subject to flares and bursts which may drive shock waves within the jet. We explore parameter space with fundamental 2D axisymmetric hydrodynamic simulations of adiabatic inviscid flow of high pressure supersonic gas, at Mach 2, from a circular nozzle into an extensive uniform gas reservoir, and consider various individual velocity bursts. By investigating the propagation of various forms of travelling shocks in the near-field, where recollimation shocks occur, we hope to systematically understand their fundamental properties and the effects on jet shock structures, before more complex simulation physics is systematically added later. The burst may also affect the surrounding lower pressure circumgalactic ambient medium, perhaps causing turbulence and/or variations in pressure (M. A. Bourne & D. Sijacki 2021; D. Prasad, G. M. Voit & B. W. O'Shea 2022). We also explore the potential for observational diagnostics

to reveal jet physics indirectly. However, any one-to-one correlations with real AGN jets would require significant additional simulation physics.

Section 2 presents the simulation method and choice of parameters used to systematically explore parameter phase-space. Section 3 presents the results, first providing a high level overview, followed by targeted simulation configurations which best exhibit the properties of shock-shock interactions. Section 4 discusses the results. Section 5 provides a summary of key conclusions, limitations of this work, and possible further work.

2 METHOD

A summary is provided here of the simulation method. More details, including the post-processing analysis tools used, can be found in sections 2 and 3 of C. Richards & M. D. Smith (2024).

2.1 Simulation set-up

As explained in Section 1, inspired by travelling luminosity knots in AGN jets, our objective here is to explore, as a first step, the fundamental physics of shock-shock interactions. We use the PLUTO code (A. Mignone et al. 2007), which utilises standardized, and non-dimensional units. We perform a range of hydrodynamic numerical simulations by injecting a supersonic jet of monatomic gas at high thermal pressure from a circular nozzle in a wall into a uniform ambient medium. Both media are taken as adiabatic, with an ideal gas equation of state. The flow is inviscid except where high gradients occur along interfaces, slip-lines, and shock-fronts where numerical viscosity is allowed to convert kinetic energy into thermal energy. As AGN jets can be relativistic and have magnetic fields, any results from these simplified simulations, or any potential observational diagnostics, could not be used to correlate with AGN jet observations without the addition of significantly more simulation physics.

Cylindrical symmetry can be assumed for our purposes, and we therefore carry out 2D axisymmetric simulations to analyse the near-field close to the nozzle. This region can result in the growth of three-dimensional surface instabilities, after the first few recollimation shocks for relativistic flows, and very low jet pressure and density ratios (A. Costa et al. 2025). However, for our chosen jet parameters and near-field consideration, surface instabilities can be neglected (J. M. Stone & M. L. Norman 1992; M. Krause & M. Camenzind 2001; M. Perucho et al. 2010; M. Perucho, J.-M. Martí & V. Quilis 2019). We also neglect jet rotation.

We choose a low Mach jet (Mach 2), with clearly defined standing-shocks, for our simplified hydrodynamic shock-shock simulations. Mach 2 is between the transonic region and the start of the hypersonic region, where standing shocks can be stretched and distorted. The general configuration follows previous work on the steady release of gas from a cylindrical nozzle at Mach 2 (M. D. Smith & T. L. Keogh 2022). We consider appropriate ranges in jet/ambient overpressure and density ratios between the two media, designated as $\kappa = p_{\text{jet}}/p_{\text{amb}}$ and $\eta = \rho_{\text{jet}}/\rho_{\text{amb}}$ respectively.

As it expands onto the grid, the jet pressure initially falls and jet velocity increases. A steady flow pattern is not established due to the initial impact onto the grid, followed by inherent oscillations in standing shocks. This is achieved by establishing a large initially uniform, reservoir which surrounds the displayed grids, both radially and axially. This is accomplished by the addition of geometrically stretched grids out to large distances. In this way

we aim to maintain a free environment that is sufficiently large so that disturbances are not trapped close to the jet, and to avoid any number of various potential computational boundary effects.

To moderate the initial jet flow impact onto the grid, we also ramp up the jet speed from zero to the final speed over 10 standardized time units (t_u ; jet-radius crossing-time at medium sound speed). However, tests have shown that the choice of between 0 and $40t_u$ for the ramp time has no effect on the final flow pattern established by $80t_u$, i.e. 40 per cent of the full simulation duration (M. D. Smith & T. L. Keogh 2022). This is when a velocity burst is introduced.

PLUTO is a grid-based code, incorporating Godunov-type shock-capturing schemes, which is publicly available (A. Mignone et al. 2007).¹ After comparing the results of numerous options, we chose a Harten–Lax–van Leer–Contact (HLLC) Riemann solver, detailed by E. F. Toro, M. Spruce & W. Speares (1994), which reconstructs an intermediate state between left and right fluid states by restoring the contact discontinuity, and a conservative time-advance predictor-corrector method, Hancock, with a Courant Friedrichs Lewy (CFL) time step number of 0.4. For reconstruction, we used a piecewise-polynomial method called LINEAR to obtain high-order left/right states at cell interfaces, with slope limiters by Van Leer.

We adapted the code initial and boundary conditions, with a reflection condition imposed on the plane from which the circular perpendicular jet flow exits and also the jet axis, and with free outflow conditions imposed on the other grid boundaries. The uniform grid has 200 radial and 400 axial zones corresponding to 15 by 30 jet radii (R_{jet}). To avoid edge effects, we extended the computational domain in the radial and axial directions by adding 100 and 200 staggered grids respectively onto the uniform section. The stretched zones are in a geometric series extending the full domain to $65 \times 130 R_{\text{jet}}$. The subsequent post-processing was performed with algorithms incorporated into IDL software.

Five properties are recorded to file at each of 1000 data-cashes, separated by $0.2t_u$, allowing evolution over $200t_u$. The parameters are the density, ρ , pressure, p , two velocity components, v_z (axial velocity) and v_r (radial or lateral velocity), and a mass-weighted jet tracer, χ . The tracer is mass weighted, with a weight of 1 for jet gas and 0 for ambient gas. This highlights the level of any mixing between jet flow and the surrounding ambient medium.

2.2 Parameters and dimensions

As a purely hydrodynamic simulation, non-dimensional units allow for ease of scaling to any size jet. The jet radius is set to $R_{\text{jet}} = 1$. By setting the ambient sound speed also to one, i.e. $c_{\text{amb}} = 1$, the unit of time, t_u , given as the jet radius crossing time at the local speed of sound, is $R_{\text{jet}}/c_{\text{amb}} = 1$. The specific heat ratio, which yields the adiabatic index, is taken as $\gamma = 5/3$, appropriate where a gas behaves with three degrees of freedom (monatomic gas). Also the ideal gas equation of state used is consistent with the generic nature of our simulations, but will require amendment if considering e.g. relativistic AGN jets. We complete the set of independent variables by setting the initial ambient density to $\rho_{\text{amb}} = 1$.

The initial sound speed,

$$c_{\text{amb}} = \sqrt{\frac{\gamma \cdot p_{\text{amb}}}{\rho_{\text{amb}}}}, \quad (1)$$

¹<http://plutocode.ph.unito.it/>

Table 1. Chosen constant inflow base-jet parameters for systematic survey of parameter phase-space.

Constant inflow jet parameters			
M (Mach no) = 2			
R (Initial jet velocity ramp-up time) = $10t_u$			
$K = \kappa$		$E = \eta$	
(Jet/ambient overpressure ratio)		Jet/ambient density ratio)	
2	8	0.1	10

yields a pressure $p_{\text{amb}} = 1/\gamma = 0.6$, and internal energy per unit volume $u_{\text{amb}} = p_{\text{amb}}/(\gamma - 1) = 0.9$ for the specific heat ratio of $\gamma = 5/3$.

2.3 Constant inflow jet parameters

The flow features will strongly depend on whether the velocity burst enters a jet with a series of oblique reflection shocks or impacts a Normal/Mach shock disc. Hence, the constant inflow jet parameters onto which a velocity burst is introduced were chosen to best distinguish between these flow patterns (see Table 1). To explore parameter space, we chose two overpressures, one low and one high, and which also encapsulate the two major shock configurations for a Mach number of 2, i.e. $\kappa = 2$ for regular reflection or oblique shocks, and $\kappa = 8$ for a prominent Mach shock disc (M. D. Smith & T. L. Keogh 2022). Extrapolation to both higher Mach numbers and other overpressures was demonstrated by M. D. Smith & C. Richards (2023). They showed corresponding changes in the distance of standing shocks from the nozzle, Mach disc sizes and oscillations in shock positions.

Although the main influence on jet flow patterns is relative jet pressure for constant inflow jets, relative jet density does play a key role e.g. in affecting the speed of jet surface waves and so influences time-dependent phenomena. Although we consider light (i.e. low jet/ambient density ratio) jets to best represent AGN jets, in order to complete our systematic survey of parameter phase-space, we investigate both light and heavy jets. Low and high density ratios were chosen to explore a reasonably large parameter space i.e. one tenth and ten times ambient pressure. One effect of changing jet density is on jet power. Sound speed is proportional to $\sqrt{\frac{1}{\text{density}}}$, so high density jets, although still Mach 2, have much lower velocities and therefore much lower powers.

2.4 Jet burst parameters

We choose three parameters to define a velocity burst, the amplitude, duration, and the associated velocity profile. Note that the jet pressure and density are unchanged so that the Mach number is proportional to the velocity.

For the profile, we superimpose a step change onto the uniform velocity with a rapid, but finite linear ramp-up, and ramp-down, over $0.1t_u$, so as to avoid any unwanted numerical anomalies. The burst is applied from $t = 80.0t_u$ i.e. once the launched jet has fully settled into the expected constant inflow configuration.

For burst duration, we distinguish three relevant types, corresponding to short, medium and long. These are defined relative to the two time scales found to scale the steady nozzle flow structure. Firstly, the dynamical time, t_{dyn} , is the time taken for the jet core matter to travel to the first/stand-off shock on the jet axis. Time-scales were derived using simple analytic formulae fitted to experimental supersonic flow results (M. D. Smith & T. L. Keogh 2022), and where C. Richards & M. D. Smith (2024)

Table 2. Chosen burst jet parameters for systematic survey of parameter phase-space.

Jet burst parameters				
B = Burst duration		V = Velocity amplitude factor		
	(t_u)		(xMach 2)	
0.5	2	10	1.4	2.0

found that this was approximately $0.5 t_u$ for a light jet. Secondly, the Kelvin–Helmholtz time is the time taken for jet surface waves to propagate along the jet/ambient interface from the nozzle to the stand-off shock location. This is approximately $4 t_u$. For heavy jets, the approximate t_{dyn} is $5 t_u$, and the surface-wave time is $15 t_u$. Based upon these times, we chose fiducial burst durations of $0.5 t_u$, $2 t_u$, and $10 t_u$, essentially short, medium, and long burst durations. We will go on to refer to these as *blast*, *prolonged-burst*, and *sustained-burst* types. We subsequently carried out a limited number of simulations with a very short burst duration ($0.1 t_u$), which we refer to as a *gust*.

Two burst velocity amplitudes were chosen in order to explore this parameter space. Firstly, a 100 per cent velocity increase i.e. $2.0 \times$ Mach speed (denoted V2.0 in simulations), and also an intermediate velocity amplitude, in this case a value of 40 per cent was chosen (denoted V1.4 in the simulations). A summary of the main parameters is provided in Table 2.

A jet simulation configuration nomenclature is used throughout the paper which states the combination of parameters used from Tables 1 and 2. For example, M2K2E0.1R10B0.5V1.4 is a Mach 2 jet, with jet/ambient overpressure κ of 2, jet/ambient density ratio of η of 0.1, jet launch ramp-up time R of $10 t_u$, burst duration B of $0.5 t_u$, and burst velocity amplitude V of 1.4. The corresponding constant-flow base-jet nomenclature is M2K2E0.1R10.

2.5 Analysis tools

Four-panel colour-scale snapshot diagrams provide a simulation overview. These display qualitative distributions of the physical parameters in the z - r plane of the cylindrical coordinates, utilising z - r distance units of R_{jet} . They show pressure, density, axial velocity, and jet tracer within the inner uniform part of the full grid.

We use cross-cut profiles of physical parameters to provide quantitative analysis of a jet at an axial position of interest, e.g. the location of a shock-shock interaction. We also study integrated quantities as a function of time. For example, a power-time graph details the jet axial and lateral energy leaving or entering the computational grid. The total power calculated is the sum of kinetic energy and enthalpy. Energy flux is found through a large concentric cylinder, at 90 per cent of the uniform grid dimensions, within the cylindrical computational domain. Axial power is calculated via the cylinder end-cap (census cap) and lateral power via the cylinder sleeve. Power units are in $\rho c_{\text{amb}}^3 R_{\text{jet}}^2$ (M. D. Smith & C. Richards 2023). Qualitative temporal pressure changes due to a burst propagation are displayed on space–time diagrams, utilising time units of t_u and distance units of R_{jet} . These can display, vertically, the pressure along the central jet axis, for all 1000 data-cashes, separated by $0.2 t_u$, for the $200 t_u$ simulation.

Last, but not least, movies provide an additional qualitative analysis tool to better understand flow patterns, and help identify and target areas of interest. They have been essential to see off-

axis dynamic effects, as well as giving a helpful overall perspective of jet dynamics.

3 RESULTS

We first systematically survey parameter space with a broad sweep of 24 simulations, using the base-jets from Table 1 and superimposed velocity bursts from Table 2. This yields an overview of properties from which we target burst jet configurations which best exhibit the properties of shock–shock interactions, utilising high time-resolution.

In order to best examine traveling-shock versus standing-shock interactions, two fiducial jet configurations were chosen, one with oblique standing shocks ($\kappa = 2$), and one with a Mach disc ($\kappa = 8$). Both were low-density ratio jets ($\eta = 0.1$), a choice in our simplified models which we consider aligns with the low density ratio nature expected of AGN jets (e.g. C. Bambi et al. 2018), without attempting to capture their full complexity. Table 3 lists the images and graphs of all simulations presented here. In addition, many of the simulation movies we produced, as well as further images and graphs, can be found in Zenodo (<https://doi.org/10.5281/zenodo.14579827>).

3.1 Jet structure and variability prior to burst

We first reviewed the four constant inflow jets, run to $200 t_u$, which act as base-jets. The four base-jet configurations were chosen to cover a wide range of jet parameters i.e. low and high jet/ambient pressure and density ratios. We then reran them with a superimposed burst beginning at $80 t_u$, i.e. once the launched jet was fully developed. Note that considerable jet variability occurs even though we inject jets at constant speed. M. D. Smith & T. L. Keogh (2022) showed that the jet flow patterns oscillate axially, and sound waves are transmitted laterally into the ambient. In this way the jet disturbs and drives ambient gas adjacent to the jet boundary surface out with it. The ambient gas is then generally replenished from the wider surroundings, resulting in a mass inflow towards the jet.

The constant inflow jet with low overpressure and low density ratio is designated M2K2E0.1R10, and is illustrated in Fig. 1 (left-panels) where weak-oblique jet reflection shock fronts are repeated across the computational grid. After the initial jet launch, energy is repeatedly cycled between kinetic energy and thermal energy through multiple regular oblique reflection shocks at locations of jet diameter expansion. The shock locations oscillate along the jet axis due to a resonant feedback loop mechanism. Jet surface waves are physically constrained to propagate at a speed closely related to the Kelvin–Helmholtz linear wave speed at the jet-ambient interface. The feedback loop has been well documented, as reviewed by (C. K. Tam 1995), and is responsible for jet screech.

The high overpressure, low density, constant inflow Mach 2 jet (designated M2K8E0.1R10) is shown in Fig. 2. A strong Mach disc is established leading to much jet turbulence downstream, as found by M. D. Smith & T. L. Keogh (2022). The kinetic energy follows a similar initial pattern as the low overpressure jet i.e. dominated by free expansion. However, the more rapid expansion results in a Mach shock disc. The disc, which undergoes larger oscillations along the jet axis, converts kinetic energy into thermal energy through a much stronger shock, where the post-shock flow becomes largely subsonic before undergoing strong acceleration back to supersonic speeds. A coherent flow pattern

Table 3. Subset of Mach 2 constant inflow and burst jet simulations presented in this paper. (Note: * 4-panel = pressure/density/velocity/jet-tracer, s-t = space-time, p-t = power-time, p-d = power-distance, prs = pressure, phys-par = physical-parameters).

Figure number	Pressure ratio κ	Density ratio η	Burst Duration t_u	Velocity V_{max}/v_o	Image/Graph*
1(left)	2	0.1			4-panel
1(right)	2	0.1	0.5	1.4	4-panel
2	8	0.1			4-panel
3	2	0.1	0.5	1.4	prs
4	2	0.1	0.5	1.4	phys-par
5	2	0.1	0.5	1.4	p-t
6	2	0.1	0.5	1.4	prs
7	2	0.1	0.5	1.4	s-t
8	2	0.1	0.5	1.4	prs
9	2	0.1	0.5	1.4	p-d
10	2	0.1	0.5	1.4	phys-par
11(left)	2	0.1	0.5	1.4	s-t
11(right)	2	0.1	0.1	1.4	s-t
12 (left)	2	0.1	2.0	1.4	prs
12 (right)	2	0.1	2.0	1.4	s-t
13	2	0.1	0.5	2.0	phys-par
14	2	10	0.5	1.4	4-panel
15	2	10	0.5	1.4	s-t
16(left)	8	0.1	0.5	1.4	s-t
16 (right)	8	0.1	2.0	1.4	s-t
17	8	0.1	2.0	1.4	prs
18	8	10	4.0	3.0	4-panel
19	8	10	4.0	3.0	s-t

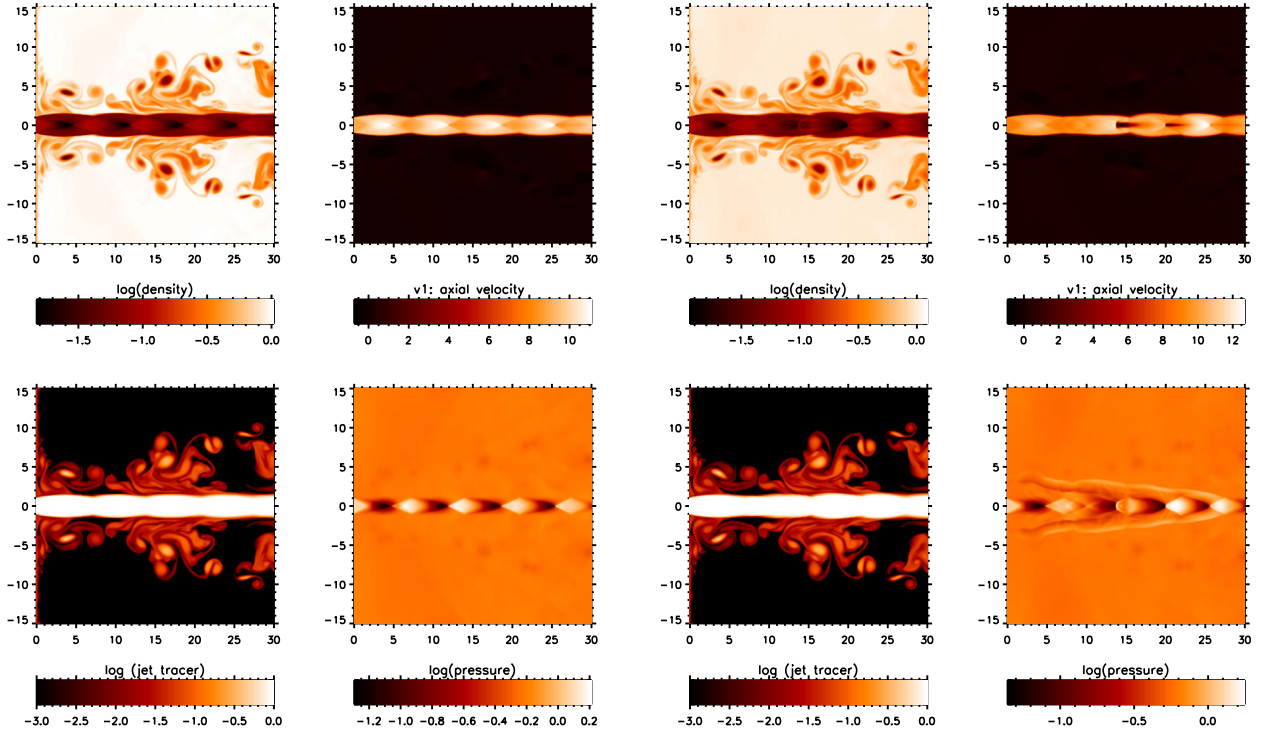


Figure 1. Comparison between a constant inflow low overpressure jet (M2K2E0.1R10) and a superimposed $0.5t_u$ duration burst (blast-type) (M2K2E0.1R10B0.5V1.4). Axes show the inner uniform grid, in standardized distance units of jet radii (R_{jet}). Physical parameters for the Mach 2 constant inflow jet, with pressure ratio $\kappa = 2$ and density ratio $\eta = 0.1$, at the instant the burst enters (at $80t_u$) (left set of panels; density, velocity, jet tracer, and pressure), and $2t_u$ after burst launch from left to right (right set of panels). The burst is best seen in the pressure image, with the burst front and rear at axial positions of $27R_{jet}$ and $13R_{jet}$ respectively, about twice the burst length after launch.

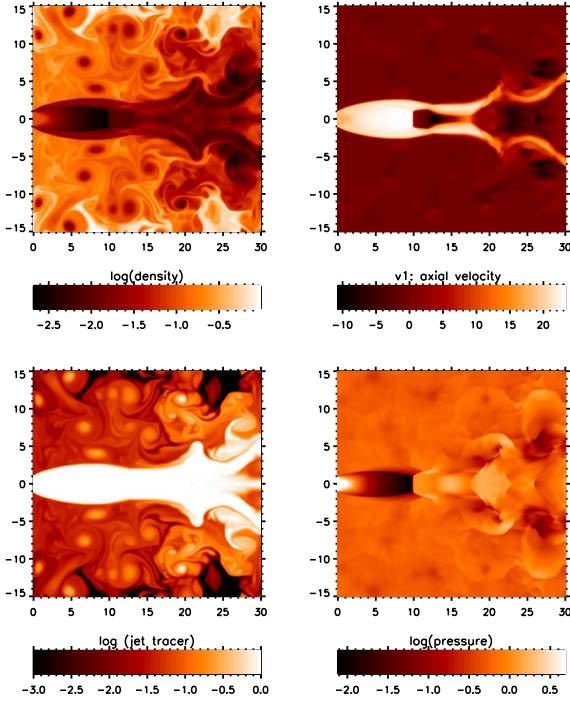


Figure 2. Constant inflow high overpressure jet flow pattern with a strong Mach shock disc. Axes are in distance units of jet radii. A constant inflow Mach 2 jet, with low density ratio ($\eta = 0.1$) and high overpressure ($\kappa = 8$) (M2K8E0.1R10), at $t = 80t_u$. The high overpressure results in a strong normal standing shock front, a Mach disc. The subsonic jet speed post-shock leads to higher acceleration, back to supersonic speeds, and more turbulence downstream, including the surrounding ambient.

is not fully regained, with the jet flow becoming highly turbulent downstream.

The high density version of the low overpressure jet, M2K2E10R10, initially establishes oblique shock structures, however normal shocks begin to dominate with an increase in associated jet turbulence. The high overpressure, high density ratio constant inflow jet, M2K8E10R10, establishes Mach discs, although turbulence is lower. Jet absolute speed, and associated jet power are also lower. Heavy jets result in lower frequency axial oscillations that are still able to create gas circulation in the surrounding gas. Denser jets grow their shear layers more slowly, and a smaller growth rate means weaker entrainment and slower development of large turbulent structures downstream of the Mach disc (D. Papamoschou & A. Roshko 1988). Images can be found in Zenodo (<https://doi.org/10.5281/zenodo.14579827>).

3.2 Burst analysis: burst along low overpressure jets

For the low density ratio (light) jet with $\kappa = 2$, the core jet speed has increased to an average of $\sim 9 - 12c_{\text{amb}}$, due to the expanding jet lowering jet pressure, and with the stand-off shock at $\sim 5R_{\text{jet}}$, yields a dynamical time of $t_{\text{dyn}} \sim 0.5t_u$. This is similar to the time-scale derived using simple analytic formula by C. Richards & M. D. Smith (2024), who also determined the corresponding longer Kelvin–Helmholtz time to be approximately $4t_u$. We found a natural division of bursts depending upon their duration which we heuristically define here, with increasing burst duration as, *gusts*, *blasts*, *prolonged-bursts*, and *sustained-bursts*. A *gust* is chosen because it affects individual standing shocks, and with a much

shorter burst length. It is a very short burst in which the impulse subsides well before the front of the wave has reached the stand-off shock ($B < t_{\text{dyn}}$). In our case ($0.1t_u$), much shorter than the short-duration, $0.5t_u$, burst from our initial systematic survey of parameter phase-space. A *blast* is chosen because it affects individual standing shocks, but with a length of the same order, and with burst duration close to the dynamical time ($0.5t_{\text{dyn}} \leq B < 2t_{\text{dyn}}$), which in our case is the short duration burst at $0.5t_u$. A *prolonged-burst* was chosen which can affect several standing shocks simultaneously, with a duration ($2t_{\text{dyn}} \leq B < 10t_{\text{dyn}}$) close to the Kelvin–Helmholtz wave speed. In our case this is the intermediate duration burst at $2t_u$, where the burst affects all standing shocks across the computational grid. For completeness, a *sustained-burst* was chosen, with a burst duration ($B \geq 10t_{\text{dyn}}$) much larger than the Kelvin–Helmholtz wave speed. In our case, the long-duration burst was $10t_u$. Since these *sustained-burst* simulations similarly affect all standing shocks across the jet axis like the $2t_u$ *prolonged-burst*, but for longer, and show very similar results, they are not reported here, but are available in Zenodo.

A central engine may temporarily flare up due to an increased accretion event. We hypothesize that this may give rise to a short impulse or velocity burst within the corresponding jets. In order to obtain an indicative approximation of burst durations for a real AGN jet which would correspond to our simple simulations, we assume estimated jet velocity from (M. D. Smith & T. L. Keogh 2022) for a M2K2E0.1 jet, with $P_{\text{amb}} = 6.35 \times 10^{-11} \text{ dyn cm}^{-2}$, $\rho_{\text{amb}} = 2.34 \times 10^{-6} \text{ gm cm}^{-3}$. We use $V_{\text{jet}} = 4.03 \times 10^9 \text{ cm s}^{-1}$, and assume $R_{\text{jet}} = 1 \text{ pc}$ with a distance to the stand-off shock is $5R_{\text{jet}}$ (as in Fig. 1). The lateral gas expansion after launch increases jet speed by about a factor of 10 (Section 3.2), i.e. $t_{\text{dyn}} = 12 \text{ yr}$. Our burst duration categorization would then correspond to the following; *gust* = 2.4 yr, *blast* = 12 yr, *prolonged-burst* = 24 yr, and *sustained-burst* = 120 yr. Clearly, such estimates are heavily dependent on assumed physical parameters. Note that in relativistic jets, time compression will affect the observed variability due to Doppler boosting (K. Kellermann et al. 2007; D. C. Homan et al. 2021).

The fiducial *blast-type* burst case is analysed in detail here considering the M2K2E0.1R10B0.5V1.4 simulation, which best illustrates shock-shock interactions. The shock crosses the computational grid in just over $2t_u$ (right sub-panels of Fig. 1). The burst-shock/stand-off-shock interaction is illustrated in the sequence shown in Fig. 3.

The blast sequence includes the following notable stages.

- (i) As the wave sets out, as a bright travelling knot, a perfect shock diamond pressure pattern awaits (left sub-panels of Fig. 1).
- (ii) The velocity burst meets and pushes out the weak oblique incident shock front, by about $1 R_{\text{jet}}$, creating reverse shock concentric conical pressure shells (centre panel of Fig. 3), where pressure increases by 80 per cent (1.1/0.6) and density increases by 30 per cent (1.3/1.0) (left panel of Fig. 4). Edge brightening would occur due to higher pressure (centre panel of Fig. 3), as the burst passes through and around the standing-shock front. The pressure remains elevated post-burst (right panel of Fig. 3).
- (iii) The burst initially widens the jet radius, by about $0.5 R_{\text{jet}}$, as it impacts the stand-off shock, with outer annulus flow passing around the shock front. Jet diameter narrows again post-shock before the burst impinges on the second standing shock (centre panel of Fig. 3).
- (iv) The pressure within the standing-shock diamond increases markedly as it is compressed by the travelling shock

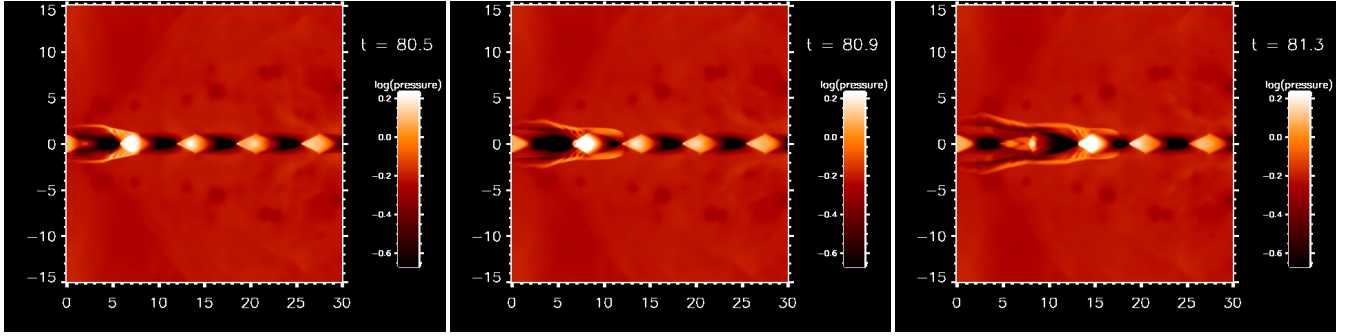


Figure 3. Early interaction of a $0.5t_u$ burst (blast-type) as it transits the stand-off shock in the low overpressure fiducial jet M2K2E0.1R10B0.5V1.4. Axes are in distance units of jet radii. Time sequence pressure snap-shots from 80.5, 80.9, and $81.3t_u$. The left panel shows the full extent of the burst from the nozzle out to $7R_{jet}$. The burst head reaches $12R_{jet}$ and $18R_{jet}$ in the centre and right panels, respectively.

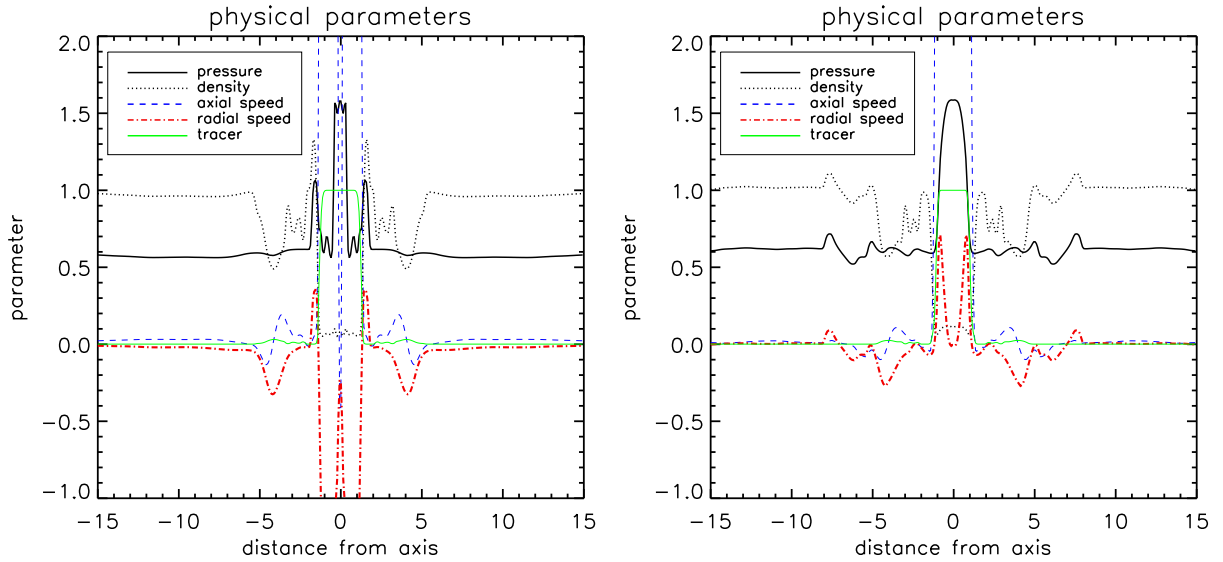


Figure 4. Radial profiles of physical quantities cutting through the stand-off shock of low density blast-type burst jet M2K2E0.1R10B0.5V1.4. Pressure and density are dimensionless, axial, and radial speeds are in R_{jet}/t_u or c_{amb} , tracer is mass-weighted (jet gas = 1, ambient = 0), and distance is in R_{jet} . The left panel corresponds to a time of $80.9t_u$ and axial distance of $6.8R_{jet}$ when the shocks are strongly interacting (i.e. middle panel of Fig. 3), resulting in high pressure concentric reverse cone shells. The right profile corresponds to the later time of $86.0t_u$, and shows how an ambient sound wave is propagating radially.

passing through and around it, and as it is forced downstream (centre panel of Fig. 3). The central pressure increases by about 100 per cent, compared to the pre-burst jet (available in Zenodo). Since luminosity is roughly proportional to pressure squared (M. Hardcastle & M. G. Krause 2013), this would result in an estimated four-fold temporary increase in luminosity.

(v) A surrounding thin sheath of high pressure moves along the jet (right panel of Fig. 3), which will travel laterally outwards, resulting in the lateral energy spike seen in Fig. 5.

(vi) The velocity burst sequentially overtakes each subsequent shock diamond, raising its pressure (and therefore luminosity), while the pressure from the earlier shock-shock interactions reduce (right panel of Fig. 3).

The consequences for the ambient medium are also significant:

(i) The wing shocks send a pressure impulse into the ambient medium (Figs 4 & 6).

(ii) A pressure wave at about 10 % above the ambient pressure then propagates at the sound speed radially outwards (right panel of Fig. 4).

(iii) Further ripples follow which contain structure (right panel of Fig. 4, Fig. 5, and across panels of Fig. 6).

Details of the shock-shock interaction at its peak (at $\sim 80.9t_u$), and the generation of radial ripples are also presented in Fig. 4 (left panel). These radial profiles cutting across the stand-off shock diamond, expanded by $0.5R_{jet}$, clearly show the pressure spikes at the jet surface (at a value of 1.1, and with density 1.3) (full lines), with a converging jet flow (red dot-dashed line in the left panel). The density depression at $\sim 5R_{jet}$ is associated with vortex rings where trapped jet gas has been entrained (centre panel of Fig. 3 at $6.8R_{jet}$ along the jet axis). In contrast, at the later time of $86t_u$, the blast has long passed and the jet profiles are re-establishing. In the ambient medium, however, a sound wave

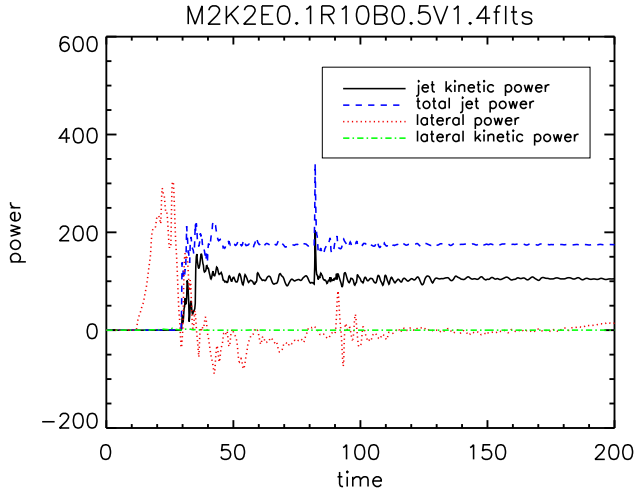


Figure 5. Power-time diagram of blast-type burst jet M2K2E0.1R10B0.5V1.4. Standardized jet power (kinetic energy plus enthalpy flux) as a function of time over the $200t_u$ simulation. Note the peak in jet power due to the velocity burst is shown by the peak in the dashed-line (blue). There is also a delayed peak in lateral power, as a strong pressure wave travels to the boundary of the outer cylinder sleeve of the computational grid at the ambient sound speed (dotted-line (red)).

makes its way out radially, followed by lesser pressure ripples as evident in Fig. 4 (right panel).

Considering beyond the stand-off shock, the right sub-panels of Fig. 1 show how the burst has penetrated the second and third standing shock diamonds and is impinging on the fourth, at $2t_u$ post-burst. We note from this figure the following:

- (i) Both the density and tracer ambient distributions are hardly altered from the non-burst simulation (comparing left and right panels in Fig. 1).
- (ii) There is essentially no exchange or entrainment of ambient or capture of jet material.
- (iii) Noticeable, qualitatively in snap shot images at various times, and clearly present in movies, are residual pressure disturbances post-burst, including the temporary appearance of some small Mach discs, which can quickly cause jet core-turbulence downstream.
- (iv) The burst has also generated axial velocity variations as the outer standing shocks are set in motion.

Although qualitative only, the overall evolution of a burst is readily revealed in a movie. Another means is the space-time diagram which displays the axial pressure profile on the ordinate and the time as the abscissa. In particular, the potential for a burst to permanently alter the flow pattern can be assessed. The left panel of Fig. 7 shows the entire $200t_u$ burst simulation. Following the burst launch at $80t_u$, the jet returns to the original quasi-steady flow pattern by about $125t_u$, leaving no obvious trace of the burst in the near-field. This is a characteristic of all the burst simulations carried out.

The movement of the burst shock and interaction with the jet standing-shocks is more clearly seen by running the code with higher time resolution over the relevant interval, e.g. between 80 and $90t_u$ as shown in the right panel of Fig. 7. The burst is seen to cross the $30R_{jet}$ grid from time $80t_u$ to $\sim 82.2t_u$. This corresponds to an average advance speed of the burst shock of $\sim 13.6c_{amb}$, and is consistent with the expected motion of

the reference frame moving with the front. The burst displaces, consecutively and temporarily, the positions of the standing shocks further along the jet axis. The second prominent feature is the rarefaction wave which accompanies the rear of the burst. The wave crosses the $30R_{jet}$ grid from $80.5t_u$ to $\sim 84.6t_u$ i.e. at $\sim 7.3c_{amb}$.

A surprising space-time feature is the bifurcation of the first and second standing shocks, at about $12R_{jet}$, creating a temporary new second standing shock at about $\sim 82t_u$. The new second standing shock is positioned at about $12R_{jet}$, with the original second standing shock moving downstream to $19R_{jet}$ by $\sim 86.8t_u$, at just over c_{amb} . This also leads to temporary Mach discs forming and promptly creating jet core flow disturbance further down stream. These are identified qualitatively in 4-panel diagrams (e.g. right velocity and pressure panels of Fig. 1), and from movies, and will be examined in detail in planned further work. Another surprising space-time feature is the split of the now third diamond into two fronts at the later time of $\sim 86.8t_u$ (Fig. 7). One at $19R_{jet}$, the second at $22R_{jet}$, both moving downstream at about c_{amb} . This is a post-burst pressure effect with a timing corresponding to Kelvin-Helmholtz jet surface waves, which travel much slower than the jet core. These waves can temporarily affect the internal jet shock structure. Fig. 8 is a snapshot during the period of backward and forward moving standing-shocks, before the jet returns to its pre-burst configuration. These delayed shocks will be investigated as part of planned further work.

Insight into the evolution can also be gained by considering the energy budget. The power output from the grid is calculated as that leaving a cylinder of axial and radial lengths 90 per cent of the uniform grid, as set out in Section 2.5. Presented in Fig. 5, this illustrates the net jet total power (from enthalpy and kinetic energy), and lateral power output for the duration of the simulation. Sound waves from initial jet launch first escape the grid laterally near the nozzle (red-dotted line) before the jet reaches the end of the axial grid at $\sim 30t_u$ (blue/black lines). The sharp peak in jet power due to the burst commences at $\sim 82t_u$, when the burst reaches the census cap near the end of the grid. A delayed peak can also be seen in the lateral power output (red dotted line) beginning at $\sim 92t_u$, consistent with the sound speed. A secondary pressure ripple occurs at $\sim 99t_u$. Post-ripple lateral power variation, 'noise', occurs as the waves transit the census cylinder sleeve.

The form in which energy is crossing the computational grid is shown in Fig. 9. The flux of each component has been integrated and presented as a function of the jet axial distance. The upper panel shows that the burst power is distributed between about 6 and $12R_{jet}$ along the jet axis, at the stand-off shock diamond, at $t = 80.9t_u$, i.e. the time of peak shock-shock interaction. Here, comparing peak with pre-peak values, the jet kinetic power has increased by $\sim 200\%$ (100 to 300 units), and enthalpy by $\sim 400\%$ (40 to 155 units). The ambient kinetic energy at this point remains small, rising from ~ 2 to about ~ 10 units, but with enthalpy increasing from ~ 20 to ~ 50 units. Therefore, the kinetic power remains almost entirely associated with the jet, and much of the energy transfer into the ambient medium is potentially through compressional thermal heating, where ambient pressure and density peak at the jet-ambient boundary (left panel of Fig. 4).

After the burst has passed the stand-off shock, the total power begins settling back to a uniform distribution with the exchange between kinetic energy and enthalpy obeying the adiabatic con-

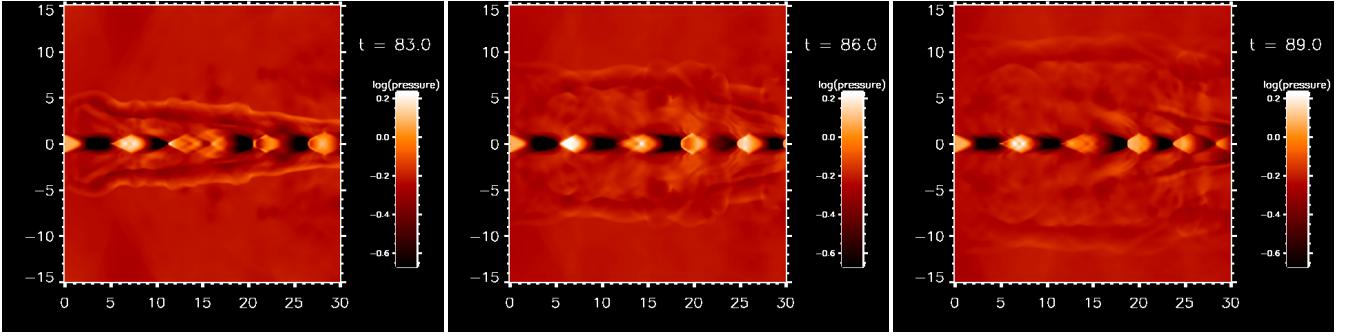


Figure 6. Radial propagation of ambient medium pressure wave caused by blast-type burst from jet M2K2E0.1R10B0.5V1.4. Axes are in distance units of jet radii. Time sequence pressure snap-shots from 83, 86 and 89 t_u . The rear of the burst is at $28R_{jet}$ in the left panel, and has left the grid in the other panels. Note the residual pressure wave, and subsequent pressure ripples, move radially into the ambient at the sound speed.

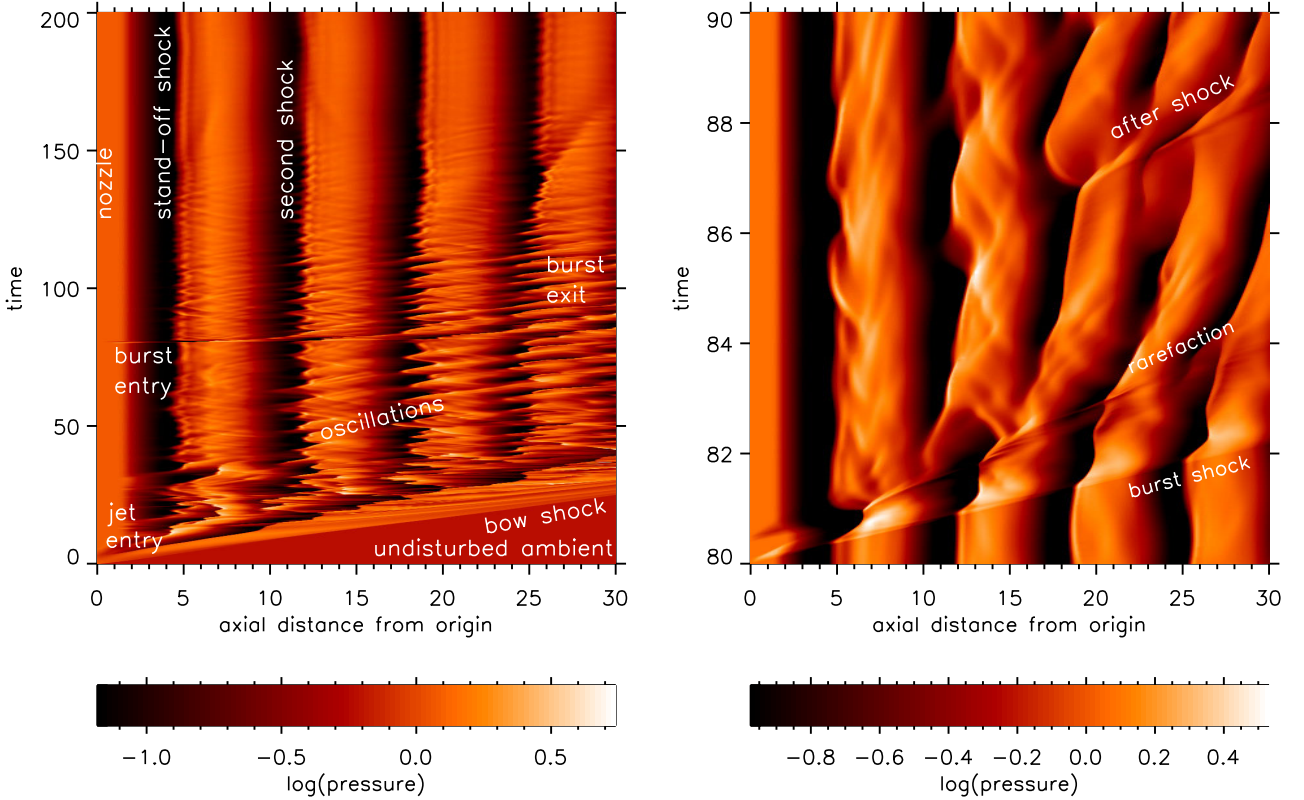


Figure 7. Space-time diagrams of blast-type jet designated M2K2E0.1R10B0.5V1.4. Panels show pressure along the jet central axis, as a function of time. Axial distance, is in jet radii. The left panel is the full simulation ($200t_u$), showing the initial jet launch (from $0t_u$ to $10t_u$), burst initiation at $80t_u$, and full flow pattern recovery post-burst. The higher time-resolution (right panel) shows the burst transit, the effect on standing-shocks, and how standing-shock locations are re-establishing before a delayed disturbance appears, about $6.8t_u$ after the burst launch, starting at the third standing shock.

dition as shown in the middle panel of Fig. 9. However, the burst energy can be seen to remain confined to a similarly small region, as it impacts the fourth standing shock (see also right pressure panel of Fig. 7).

The lower panel of Fig. 9 shows the final kinetic energy and enthalpy variations along the jet axis at the end of $200t_u$ simulation. The panel shows that regular reflection shocks, where kinetic energy and enthalpy are exchanged, are re-established i.e. confirming that the burst does not permanently disrupt the internal jet shock structure in the near-field, consistent with all other simulations.

Fig. 10, for burst jet simulation M2K2E0.1R10B0.5V1.4, provides further details necessary to understand the shock-shock interactions during the propagation of a *blast* across the first, stand-off, divergent-convergent region. With a burst duration of $0.5t_u$, and amplitude V1.4, the four panels display both the initial shock entry and the subsequent changes, where we plot the jet parameters as a function of distance from the nozzle. Note that the velocity and density are relative to the pre-burst nozzle values for display purposes. Also, note in the bottom panel the transient increase in pressure at the shock-shock interaction at this time, would yield roughly a three-fold increase in luminosity.

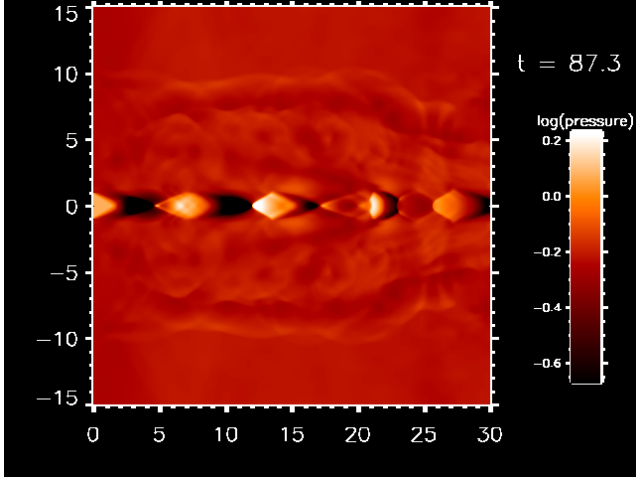


Figure 8. Pressure distribution at time $87.3t_u$ for the blast-type burst simulation M2K2E0.1R10B0.5V1.4. Axes are in distance units of jet radii. This snap-shot corresponds to the period of delayed disturbance to jet shock structures post-burst, illustrated in the right panel of Fig. 7.

3.2.1 Burst duration variation: gust, blast & prolonged-burst

The left panel of Fig. 11 displays the blast progression with time in a space–time diagram. The burst starts in the lower-left corner (at coordinates $z = 0.0R_{jet}$, $t = 80t_u$) and drives a shock into the jet. It stops after $0.5t_u$ (coordinates $z = 0.0R_{jet}$, $t = 80.5t_u$). From this point, a rarefaction wave starts as sound waves mediate the growing gap between the faster burst gas and the following lower speed gas. In the meantime, the advancing shock has caught up to the apex of the first standing-shock diamond (at $z \sim 5R_{jet}$, $t \sim 80.4t_u$). The faster burst material is compressed against this, creating a high pressure knot in which the apex has been flattened. The rarefaction wave reaches the knot (at $z \sim 6.2R_{jet}$, $t \sim 81.0t_u$), after which the first diamond shock regains its shape.

The main result is that the burst can be followed through the existing standing-shocks which remain dominant, temporarily energising them (comparing top and bottom panels of Fig. 9). The interaction can be sufficient to temporarily alter a shock from a regular reflection to a small Mach shock disc, but not altering their axial positions significantly. In addition, the burst has a minor ephemeral influence on the jet/ambient interface. Hence, although a sound wave is transmitted into the ambient, along with some following small amplitude ripples, they are not of significance.

The number of standing-shocks through which a burst can be followed is of interest. A burst dissipates as it progresses downstream due to finite duration and the passage of the rarefaction wave. More relevant, energy is rapidly converted to thermal across the front of the burst while the velocity jump remains steep. In the absence of variable radial expansion due to the overpressure, we would expect the burst and pre-burst gas to be divided by a tooth-like velocity structure which connects the gas past through the reflected shock in the burst to the gas shocked by the advancing velocity burst. This would imply an advance speed of the interface roughly intermediate between the jet and the burst.

A potential diagnostic measurement is the distance that a burst travels downstream while maintaining a measurable disturbance. In an overpressured jet, this is related to the number of standing-shocks through which a burst passes. A burst diminishes in

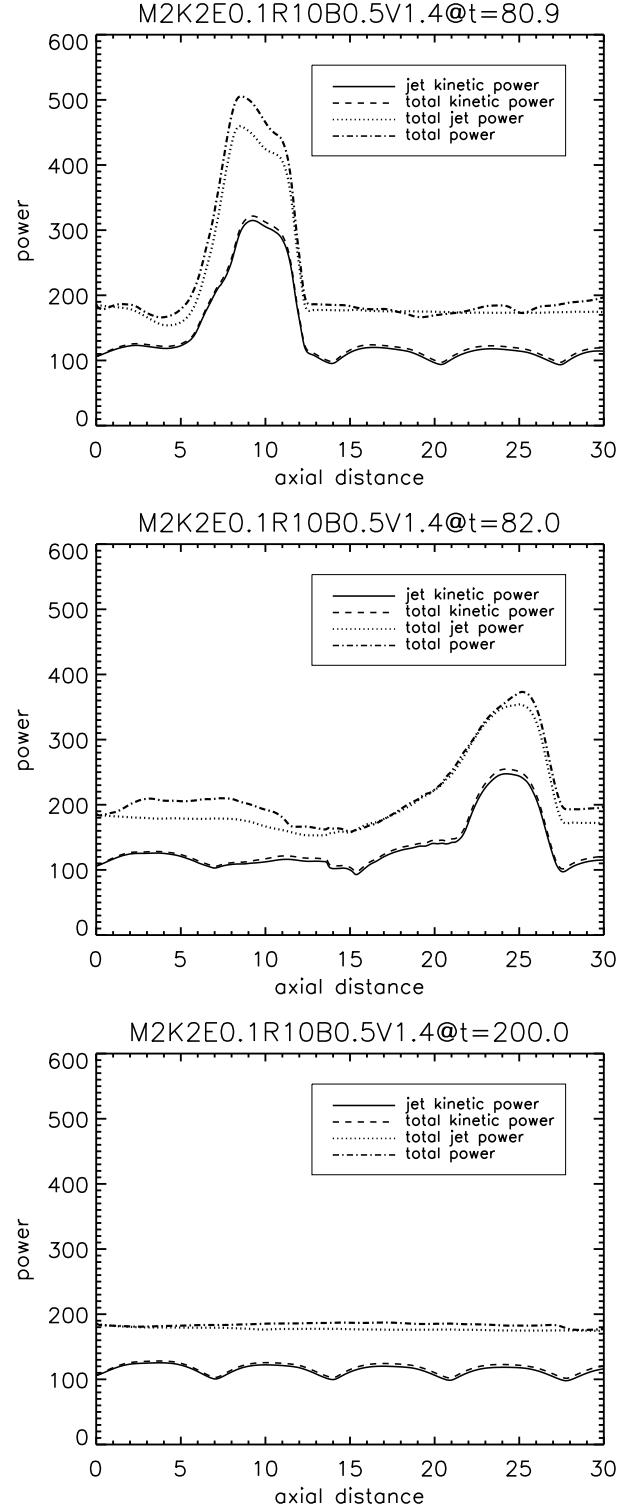


Figure 9. Variation between jet kinetic energy and enthalpy along jet M2K2E0.1R10B0.5V1.4. Power is in standardized units, as well as axial distance (jet radii). The top graph is at $80.9t_u$ i.e. capturing the shock-shock interaction with the stand-off shock. The middle graph is at $82.0t_u$, where the burst impacts the fourth standing shock, near the end of the computational grid. Finally, the jet dynamics, of regular reflection shocks, have returned to pre-burst conditions at the end of the simulation at $200t_u$ (bottom graph).

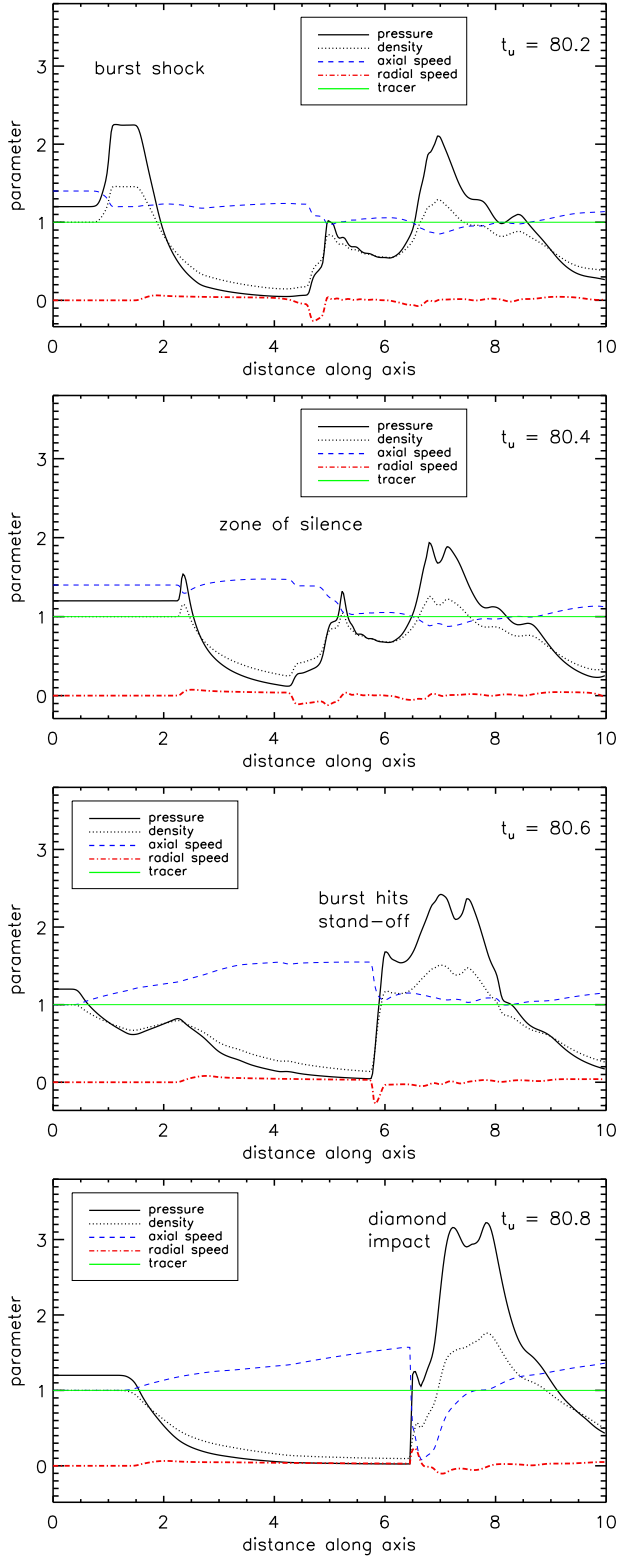


Figure 10. Profiles showing variations along the low overpressure low density blast-type jet M2K2E0.1R10B0.5V1.4 close to the central jet axis for a blast starting at time $80t_u$ and lasting $0.5t_u$. Parameters are in standardized units. Axial distance is in units of jet radii. The panels cover the first $0.8t_u$ after burst launch. The increase in the stand-off shock pressure (bottom panel) would correspond to roughly a three-fold increase in luminosity.

strength as it progresses downstream due to the reverse shock in front and the rarefaction wave at the rear.

We note that the advancing shock is strongly affected by the radial expansion between the nozzle and stand-off shock (second panel of Fig. 10). This radial rarefaction quells the pressure jump, where expansion dominates. On the other hand, the burst is not able to maintain the high pressure for long, with the kinetic energy being turned into thermal energy, as the burst drives into the jet, within about $0.5t_u$ in a distance $\sim 5R_{\text{jet}}$. As shown in the left hand panel of Fig. 11, this means that the burst generates a brightening of the first standing-shock diamond, by the subsequent higher pressure post-shock. However, it does not substantially alter its location. The following shock diamonds are also not significantly perturbed/displaced. The right hand panel of Fig. 11 illustrates the effect of a gust-type burst ($0.1t_u$ duration). The less energetic, shorter duration, gust-type burst causes less standing-shock disruption, as expected.

A *prolonged-burst* of $2t_u$ persists far downstream accelerating and brightening all the knots in the field near the nozzle, to varying degrees, as shown in the left panel of Fig. 12. The snapshot at time $t = 82t_u$ captures the phase when all the knots possess enhanced pressures simultaneously. However, the effect of the prolonged burst on the stand-off is most remarkable. As shown in the right-hand panel of Fig. 12, the continued ramming of the burst for $2t_u$ relocates the stand-off shock, $\sim 2R_{\text{jet}}$ downstream. However, once the rarefaction wave at the rear of the burst catches up with the stand-off, the stand-off shock bifurcates into two separate regular reflections, and where the original second shock diamond becomes the third shock diamond.

This prolonged burst also has an effect on the ambient medium. By raising the ambient pressure, the stand-off shock moves towards the nozzle even before the burst has terminated. A pressure wave is also seen to transit radially away from the axis at the ambient sound speed while internal jet after-shocks persist, left panel of Fig. 12.

The Kelvin–Helmholtz time is the time scale for surface waves to propagate between the nozzle and the stand-off shock. The time scale is about $4t_u$ for density $E0.1$ as calculated by M. D. Smith & T. L. Keogh (2022). This implies that there is sufficient time for the prolonged burst discussed here to re-structure the channel walls.

3.2.2 Burst amplitude variation

Fig. 13 shows radial profiles for the *blast-type* jet, with an increased burst speed (i.e. M2K2E0.1R10B0.5V2.0). This displays the physical parameters at $6.8R_{\text{jet}}$, the location of the high pressure concentric reverse cone shells at the stand-off shock. A summary comparison with the blast simulation M2K2E0.1R10B0.5V1.4 is provided in Table 4.

The stand-off oblique shock undergoes a similar transition to the M2K2E0.1R10B0.5V1.4 jet, but is displaced about $1R_{\text{jet}}$ further along the jet axis by the higher energy burst. The pressure images show similar higher pressure surrounding the jet boundary, although the high pressure concentric reverse cone shells are not as clearly defined.

3.2.3 Jet density variation

Heavy (high density ratio) jets were considered as part of the systematic survey of parameter phase-space. As explained in Sec-

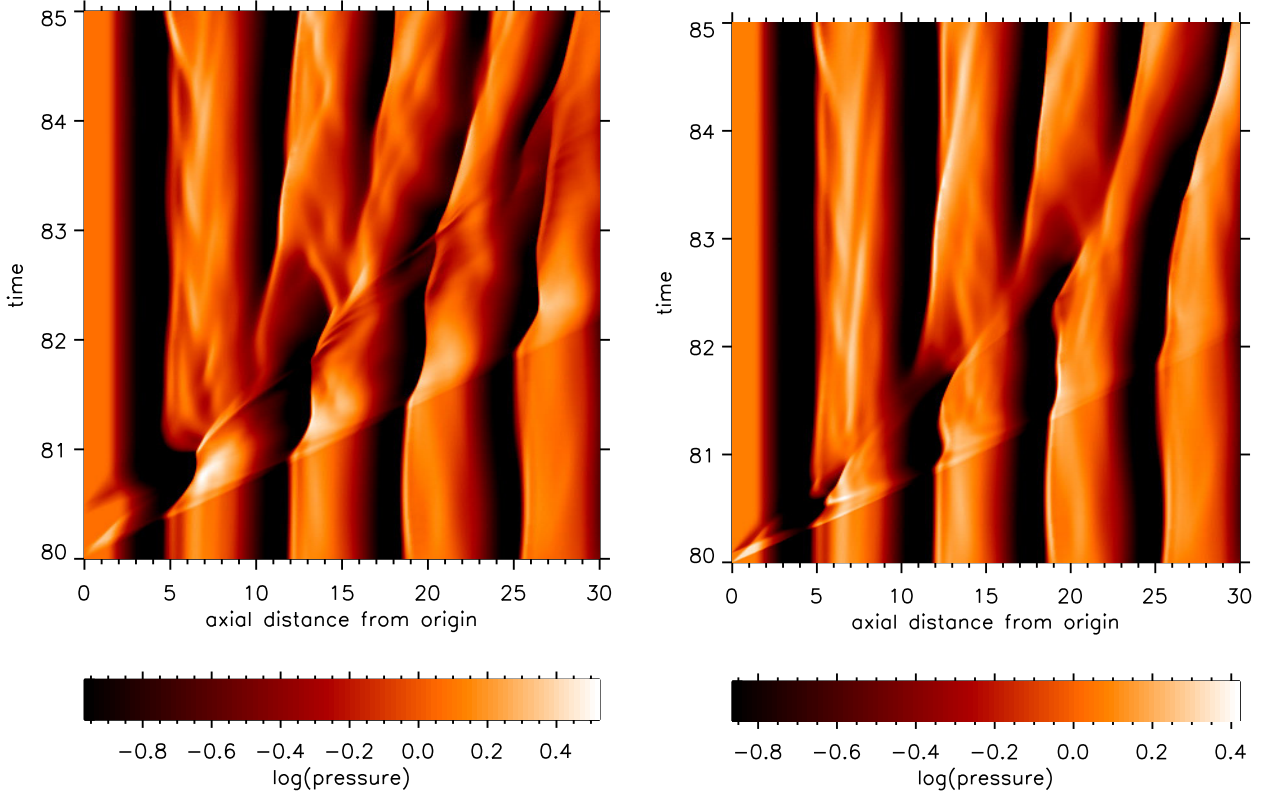


Figure 11. Space-time diagrams of pressure during a burst along the jet axis for blast-type (left) and gust-type (right) simulations denoted M2K2E0.1R10B0.5V1.4, and M2K2E0.1R10B0.1V1.4, respectively. Axial distance is in units of jet radii. A velocity burst initiates at $t = 80t_u$. In the left panel, the *blast* ($0.5t_u$ burst) traverses the jet in about $2t_u$, temporarily forcing successive standing shocks further along the jet axis. In the right panel, the less energetic, shorter $0.1t_u$ duration gust-type burst causes less standing-shock disruption, as expected.

tion 2.3, a heavy jet has a low speed for a given pressure and Mach number due to the associated lower sound speed in a denser gas. Hence, a burst traverses relatively slowly in units of the ambient sound speed. The result is that a bow shock is driven into the surroundings as the burst moves down the jet, rather than the pressure ripples for a light jet. This is illustrated in Fig. 14, for jet M2K2E10R10B0.5V1.4. This is a gust-type burst in this heavy jet, with burst duration much less than the t_{dyn} of $4t_u$. The burst is visible as it just reaches the stand-off shock after a time of $4t_u$ in the left sub-panels. After a time of $12t_u$, it has reached $\sim 18R_{\text{jet}}$ (right sub-panels).

Before the *gust* enters, oblique-shocks are established, with Mach discs forming further down stream. The Mach discs quickly make the remaining jet unstable, with relatively large axial oscillations in standing-shock positions. The complete simulation space-time diagram, on the left side of Fig. 15, shows the stable stand-off reflection shock and the further axially oscillating standing-shocks which are present throughout. Both the initial advance of the working surface and the shock-induced pressure knots possess the same speed. The rate at which the jet channel can be reconfigured due to changes in κ or M_{jet} is determined by the jet Kelvin–Helmholtz wave speed at the boundary between the jet surface and adjacent ambient. An analytic approximation of Kelvin–Helmholtz wave speed obtained from M. D. Smith & T. L. Keogh (2022) is

$$V_{\text{KH}} = v_{\text{jet}} \frac{\eta}{1 + \eta}, \quad (2)$$

where v_{jet} is the jet velocity, and η the jet to ambient density ratio. This wave speed and the distance to the stand-off shock then yields the channel reconfiguration time scale for our analysis. Here, this is calculated as $0.68c_{\text{amb}}$ to a first approximation.

The effect of the burst can be seen in the higher time-resolution space-time diagram on the right of Fig. 15, which indicates the dynamical time scale for the heavy jet is about $4t_u$. This panel indicates how the gust propagates across the grid in about $20t_u$, i.e. with a speed of $1.5c_{\text{amb}}$, while the Kelvin–Helmholtz surface wave has a speed of $0.6c_{\text{amb}}$. As opposed to a *blast*, a *gust* does not significantly reposition, temporarily, the recollimation shocks.

3.3 Burst analysis: burst along high overpressure jets

A Mach shock disc characterizes jets of high overpressure. This stand-off shock tends to be highly variable with a turbulent plume downstream in the case of very high overpressures. Here, we start with analysis of the $\kappa = 8$, light jet, simulation (M2K8E0.1R10B0.5V1.4). This has a clear stand-off Mach disc, as shown in Fig. 2, at $t = 80t_u$, as the burst is about to enter the jet.

We may expect our definition of burst duration i.e. *gusts*, *blasts*, and *prolonged-bursts* to remain valid since the dynamical time and Kelvin–Helmholtz times for the $\kappa = 8$ jet, $0.56t_u$ and $4.72t_u$, respectively, are similar to those of the $\kappa = 2$ jet, $0.48t_u$ and $3.96t_u$ respectively, (C. Richards & M. D. Smith 2024). The stand-off Mach disc is located further from the nozzle as the overpressure is increased, however the jet speed is also increased in proportion.

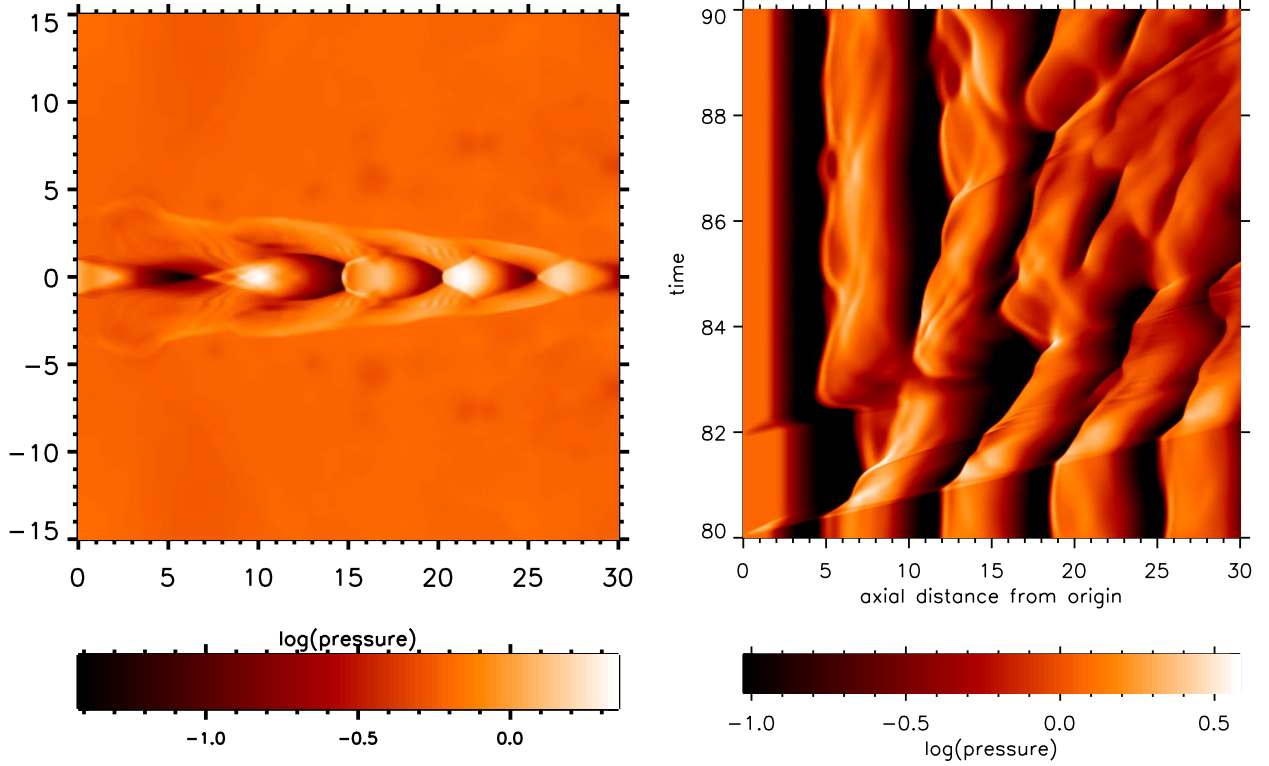


Figure 12. *Prolonged-burst* jet M2K2E0.1R10B2V1.4. Axial distance is in units of jet radii. The pressure image (left panel) is at $t = 82.0t_u$, capturing the entire $2t_u$ velocity burst. Simultaneous high pressure concentric reverse cone shells are established simultaneously against the first three oblique reflection shocks, for this *prolonged-burst*. The space-time diagram (right panel) shows the effect on all standing-shocks as well as the disruptive effect of the delayed Kelvin-Helmholtz jet surface wave.

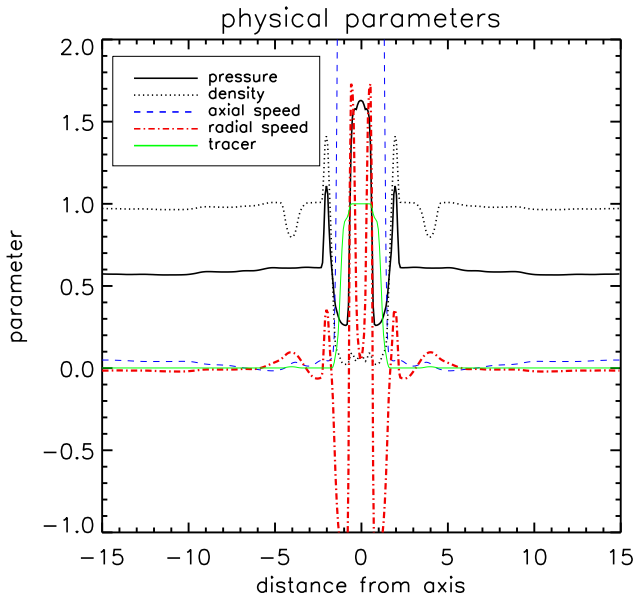


Figure 13. Blast-type jet M2K2E0.1R10B0.5V2.0 physical parameter graph at $6.8R_{jet}$ and $t = 80.9t_u$. Radial distance is in units of jet radii. This location, at the stand-off shock, is where high pressure concentric reverse cone shells are located at the peak of the shock-shock interaction. Note the peak in density and pressure at $\sim 1.5 R_{jet}$ radius.

Table 4. Comparison of physical parameters for *blast*-type velocity burst in M2K2E0.1R10 Jet with different amplitudes.

Velocity Burst	Fig.	Pressure Peak*	Density Peak*	Jet Radius (R_{jet})	Axis Disp. (R_{jet})
B0.5V1.4	4	1.1(+80 %)	1.3(+30 %)	~ 1.5	~ 1.5
B0.5V2.0	13	1.1(+80 %)	1.4(+40 %)	~ 2	~ 2.5

*at jet-ambient boundary.

To illustrate the effect of a burst on a high overpressure, low density ratio jet, Fig. 16 presents space-time diagrams of burst jets simulations M2K8E0.1R10B0.5V1.4 and M2K8E0.1R10B2V1.4, comparing a *blast* with a *prolonged-burst*. From the overview of the entire simulations (upper panels), there is much jet turbulence down stream, resulting in limited post-burst disturbances, compared to the low overpressure burst jets. Compared to the low overpressure fiducial burst jet, there is no noticeable effect of the subsequent slower Kelvin-Helmholtz jet surface wave, with a dynamical time of $\sim 5t_u$, in this highly turbulent jet.

The immediate effects of each burst is displayed in high time-resolution in the lower panels of Fig. 16. We find the *blast* transit through the existing flow pattern with notable temporary repositioning of the Mach discs, by $3R_{jet}$ and $7R_{jet}$, respectively (see Table 5). A *prolonged-burst* is necessary to significantly relocate the Mach disc. A strong Mach disc shock is more resilient than the oblique shock pattern, for similar burst amplitude and duration, due to the higher jet pressure post-shock (e.g. $\sim 40\%$ higher at the

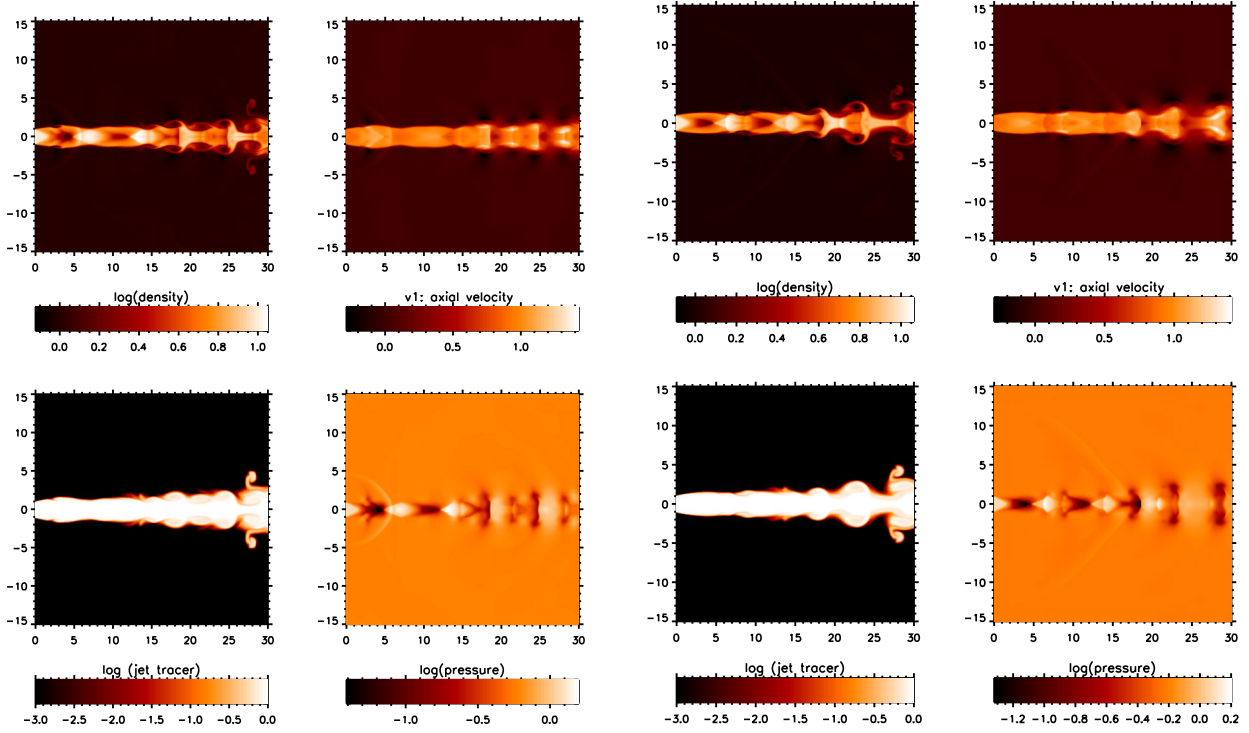


Figure 14. The stand-off shock of heavy burst jet M2K2E10R10B0.5V1.4 is just beginning to be affected by a $0.5t_u$ gust-type burst at a time of $84t_u$ (left panels), and after at $92t_u$ (right panels). Axes are in standardized units of jet radii. The Mach 2 jet has a density ten times ambient density ($\eta = 10$), and low overpressure ($\kappa = 2$), where the inner shocks contain sub-structure and a bow wave propagates into the ambient medium as a result of the gust-type burst.

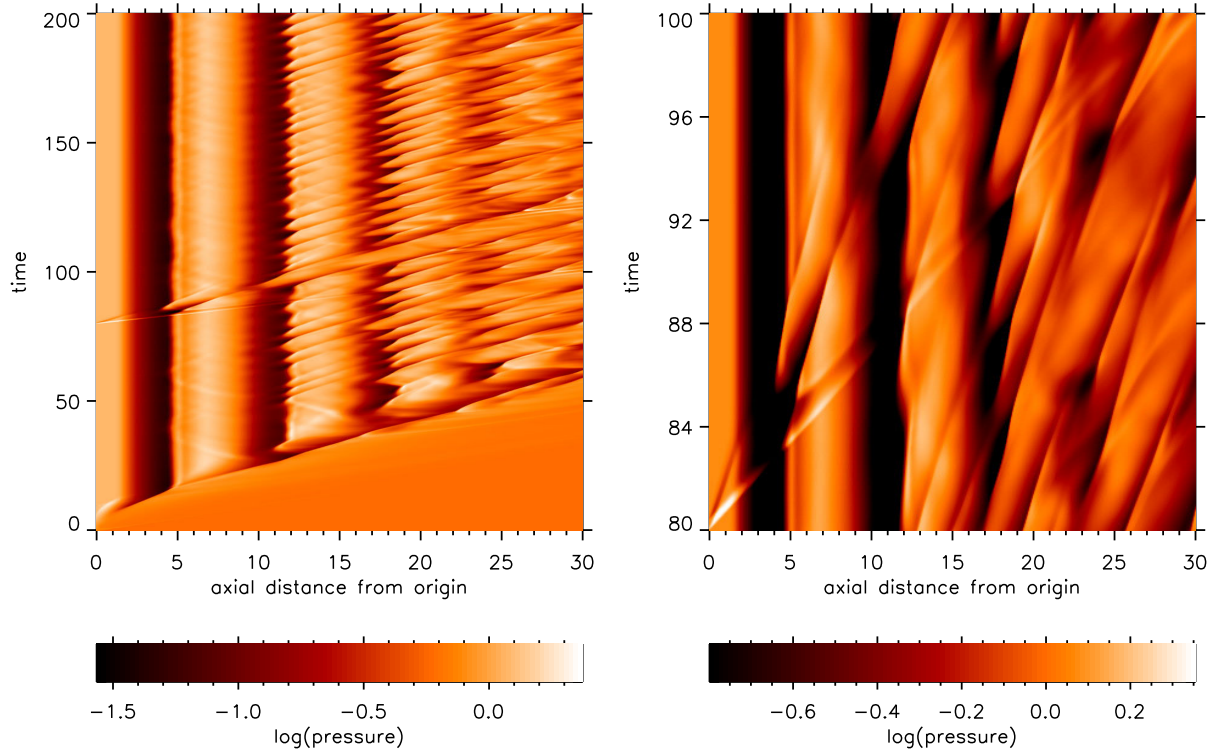


Figure 15. Pressure space-time diagram of low overpressure heavy gust-type burst jet M2K2E10R10B0.5V1.4. Axial distance is in units of jet radii. The temporary disturbance caused by the velocity burst, from $80t_u$, can be seen in the full simulation (left panel). After the more stable stand-off reflection-shock, there are low frequency oscillations of standing-shocks (as normal) in this low velocity, high density jet, which are restored post-burst. The right panel shows, in higher time-resolution, the passage of the burst and details of the disruption to standing-shocks.

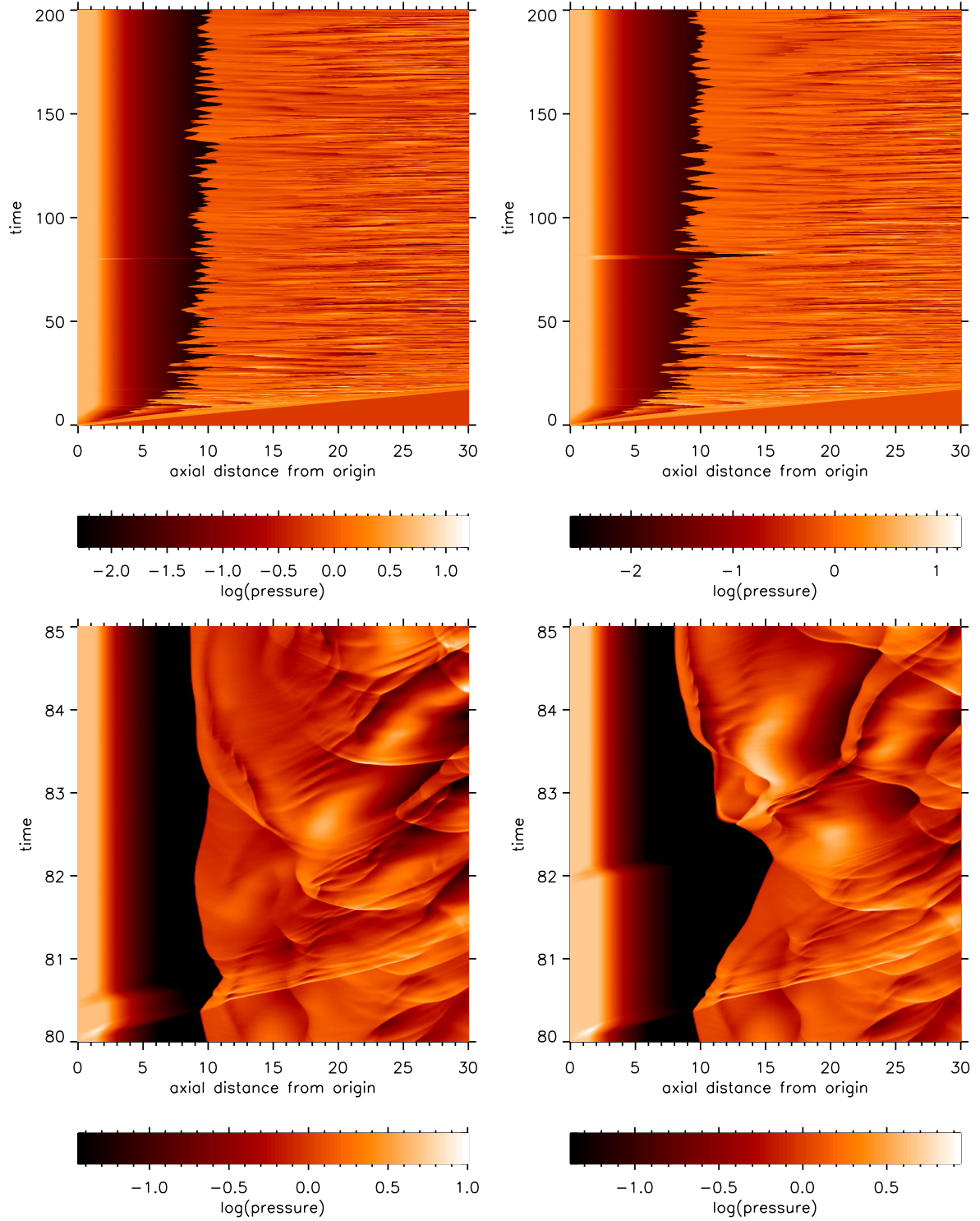


Figure 16. Space-time diagrams for high overpressure burst-jets M2K8E0.1R10B0.5V1.4 and M2K8E0.1R10B2V1.4, each containing a stand-off Mach shock disc. Axial distance is in units of jet radii. The jet overpressure is $\kappa = 8$ for each jet, and where a burst enters at $80t_u$. The left panels show a blast-type burst with duration of $0.5t_u$ (M2K8E0.1R10B0.5V1.4). The right panels show a prolonged-type burst with duration $2.0t_u$ (M2K8E0.1R10B2V1.4). The upper panels give an overview of each entire simulation. The lower panels provide high time-resolution of the immediate burst effects. In each case, the stand-off Mach disc is forced along the jet axis by the velocity burst, further for the longer duration burst. Each Mach disc repositions itself promptly after the burst has passed, with minimal post-burst disturbances.

Table 5. Standing Shock Displacements for Similar Burst Duration and Amplitude in Low and High Overpressure Jets.

Standing shock displacements	
Burst simulation	Approximate axial displacement (R_{jet})
M2K2E0.1R10B0.5V1.4	1.5 (Fig. 7 - right panel)
M2K2E0.1R10B2.0V1.4	3 (Fig. 12 - right panel)
M2K8E0.1R10B0.5V1.4	2 (Fig. 16 - bottom left panel)
M2K8E0.1R10B2.0V1.4	7 (Fig. 16 - bottom right panel)

jet axis for M2K8E0.1R10B0.5V1.4 compared to the third graph of Fig. 10), as well as a step change in pressure rather than a more gradual increase. The disc provides more resistance to a burst crossing the shock front, and is displaced further along the jet axis as a result, compared to weak oblique shock. Both near-field flow patterns return promptly to pre-burst conditions, with brief residual energy trails. However, the longer duration burst does takes more time to return to pre-burst conditions.

Pressure snapshots as a *prolonged-burst* navigates across the near field in burst simulation M2K8E0.1R10B2V1.4 are displayed in Fig. 17. The sequence covers a time period of 80.0 to 84.0 t_u . High pressure concentric reverse cone shells impinge on the stand-off shock, as jet pressure increases locally as a result of the velocity burst being compressed against the high pressure, high density, shock front. The jet radius widens initially (by about 1 R_{jet}) as the burst first impacts the stand-off shock, and then narrows to about 0.5 R_{jet} as the burst preferentially flows around, rather than through the Mach disc. The position of the stand-off Mach disc moves out far along the jet axis (by 7 R_{jet}) as the velocity burst transits. It then returns to its pre-burst position, where it resumes its normal axial oscillations of plus/minus 1 R_{jet} . In reversing its direction, back towards its normal standing-shock position, the Mach disc enlarges again to its original pre-burst size. Subsequent post-burst high pressures develop briefly down stream of the Mach disc i.e. brief residual energy trails. Residual jet pressure variations have not quite settled down at 85 t_u . The jet remains highly turbulent post stand-off shock, and the jet is not permanently disrupted by the burst. The transit of the velocity burst, results in a pressure shell developing around the jet. This sends out a sound wave (pressure ripple), but unlike the low overpressure jet, the subsequent features are hidden within the highly turbulent ambient.

Qualitatively, the movie of jet pressure variations confirms how the burst results in multiple transient Mach discs being temporarily established. This results in trailing jet features post-burst, although for a much shorter period compared to the low

overpressure jet. Post burst, the Mach disc moves back along the jet axis to its pre-burst position, temporarily reducing in diameter and undergoing some distortion, before returning to its pre-burst size. The movies and additional images and graphs are available on Zenodo (<https://doi.org/10.5281/zenodo.14579827>).

As part of our exploration of parameter phase-space, we examined a longer, higher velocity burst, in a heavy high overpressure jet (M2K8E10R10B4V3) (Fig. 18). For this slower heavy jet, the burst is a *blast*-type since burst duration is similar to the jet dynamical time of about 5 t_u . We found the high amplitude and prolonged increase in jet velocity is inherently different to the low overpressure burst jets considered above. In this case, the burst drives out a new working surface and bow shock. The stand-off shock is significantly displaced along the jet axis (some 16 R_{jet}) when the advancing burst traverses, and only returns after the effects of the burst have dissipated. The left panels display the initial entry of the burst and the right panels show the altered flow pattern at the end of the *blast*-type burst. Fig. 19 presents the space-time diagram for 20 t_u after burst launch. It shows that the pressure rises rapidly as the high velocity step change meets the Mach disc, remaining at this level while moving the Mach disc with it. The figure also shows a rarefaction wave helps to restore the jet dynamics post-burst.

4 DISCUSSION

The rapid propagation of bursts and pulses down astrophysical jets has been studied in many contexts (L. Kofman & A. C. Raga 1992; M. D. Smith, G. Suttner & H. Zinnecker 1997; J. M. Stone & P. E. Hardee 2000; M. Böttcher & C. D. Dermer 2010; E. L. Elley et al. 2026). Perturbations included analytic velocity variations, colliding relativistic shells, magnetic hydrodynamic simulations of travelling density plus velocity top hat profiles, and relativistic hydrodynamic simulations of travelling shocks due to jet power variability. These are generally considered to be contained within a channel, equivalent to the gusts and blasts explored here. In terms of prolonged bursts, however, multiple episodes of jet activity, as opposed to knots in an underlying jet, dominate the structure of some radio galaxies (C. Brocksopp et al. 2007; V. Singh et al. 2016; K. Chavan, P. Dabhade & D. J. Saikia 2023).

A second line of research involves standing shocks internal to the jet. In most works, this is a consequence of recollimation of a supersonic jet (M. Perucho & J. M. Martí 2007; Y. Y. Kovalev et al. 2020a; M. D. Smith et al. 2025). Y. Y. Kovalev et al. (2020a) note that the recollimation domain is the preferable location for standing shocks, and found in the comprehensive MOJAVE anal-

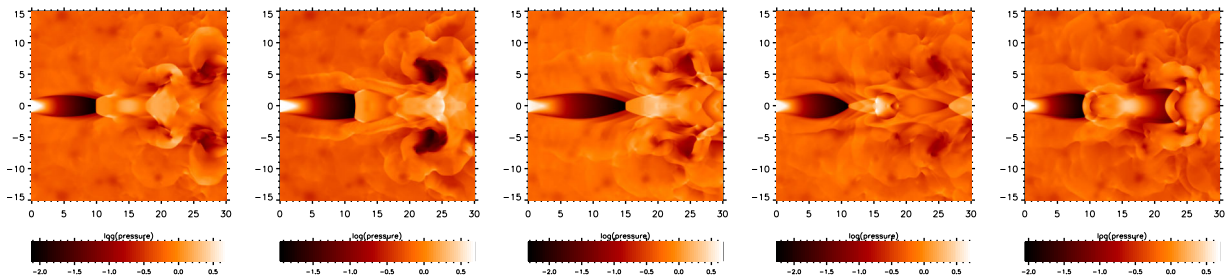


Figure 17. *Prolonged-burst* jet M2K8E0.1R10B2V1.4 time sequence pressure snapshots at 80.0, 81.0, 82.0, 83.0 and 84.0 t_u . Axes are in units of jet radii. The Mach disc shock is temporarily forced far out along the jet axis with high pressure concentric reverse cone shells formed by the shock-shock interaction. An expanding pressure shell also forms around the jet as the velocity burst passes, sending a sound wave out into the highly turbulent ambient.

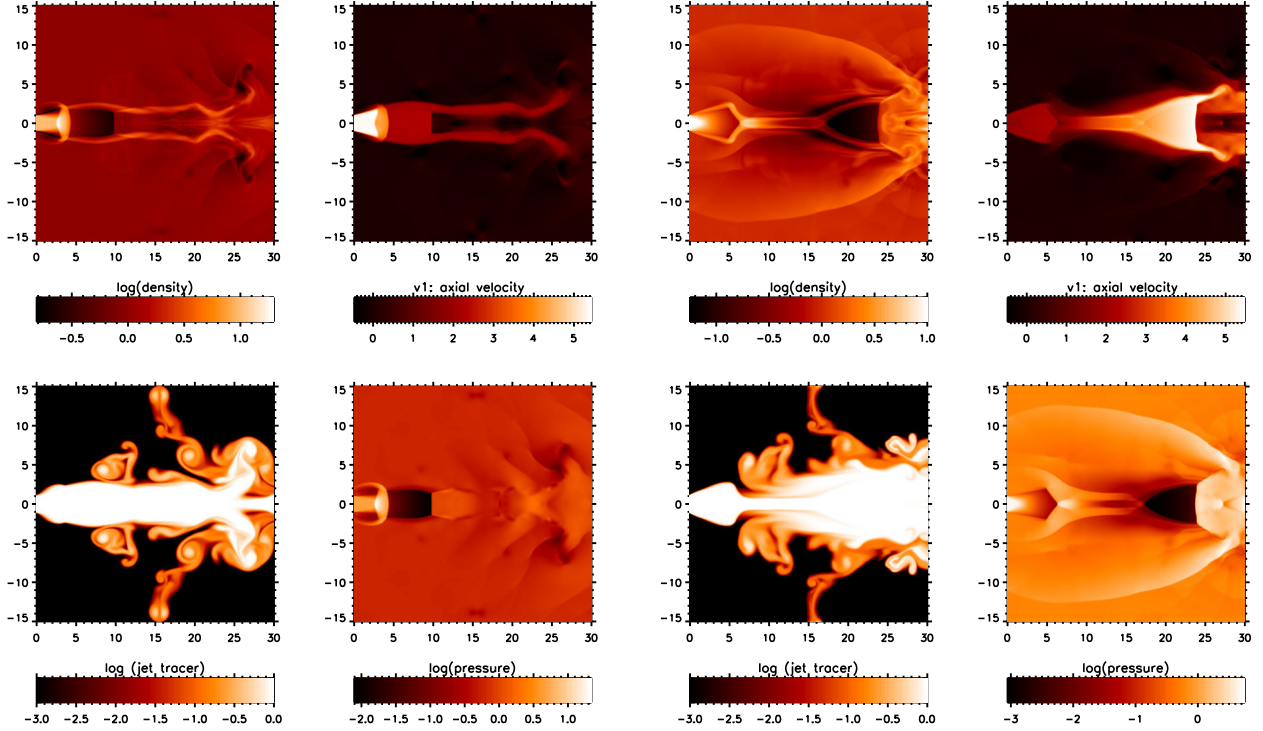


Figure 18. Physical parameter snapshots as a blast-type burst enters the jet (left panels), and at $4t_u$ approaches the far end of the uniform grid (right panels) of high overpressure heavy jet M2K8E10R10B4.0V3.0. Axes are in units of jet radii. With $\kappa = 8$, a Mach disc is established. At $84t_u$ the burst temporarily establishes a single thick high pressure reverse cone shell on the outer annulus of the significantly displaced stand-off Mach disc.

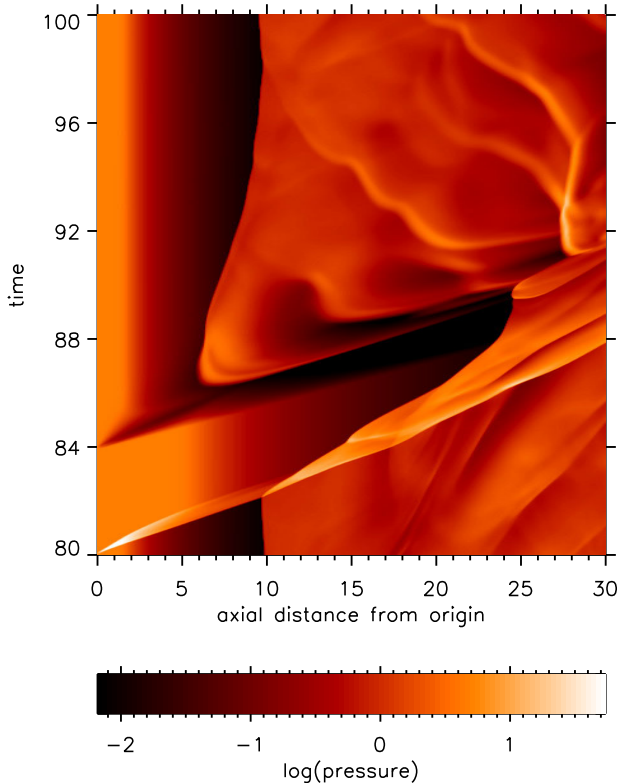


Figure 19. Space-time diagram of a blast-type high speed burst in heavy high overpressure jet M2K8E10R10B4.0V3. Axial distance is in units of jet radii. The Mach disc is displaced along the jet axis some $16R_{jet}$.

ysis of M. L. Lister et al. (2018a). The nature and stability of stationary shocks in overpressured jets has also been investigated by Y. Mizuno et al. (2015) and S. Boula et al. (2025).

Our approach here combines the two above approaches, with both a burst and recollimation shocks interacting in a jet. Although we are necessarily restricted in complexity here, we mention that many recent works focus on aspects of three-dimensional magnetohydrodynamic and relativistic jets over relatively short evolution times (e.g. R. Pal & A. Roy 2026; S. Boula et al. 2025). We restrict this study to the physical consequences in a generic sense to uncover fundamental features.

We consider that a collimated burst of energy, travelling along a jet, could accompany a step change in the accretion rate of a central compact object (M. Spada et al. 2001; Y. Coronado, O. López-Corona & S. Mendoza 2016). Equating such a burst to a temporary jump in jet speed is not obvious. Jet expansion from within a confining core would convert thermal into kinetic energy, and increased magnetic strength could increase jet flow acceleration, density, etc. Hence, although not the only factor which needs to be explored, we consider simulations where we systematically explore parameter space and can examine the fundamental physics of velocity burst travelling-shock to standing-shock interactions. These may infer potential underlying diagnostics for AGN jets. However, additional and more specific simulation physics are needed before any correlations with travelling luminosity knots in real AGN jets could be made.

In this section, we discuss the significance of our findings of the jet velocity burst simulations presented in Section 3.

4.1 Jet flow patterns

As part of our systematic exploration of parameter space, we considered velocity bursts of varying durations and amplitudes along Mach 2 jets only, which have clearly defined standing-shock patterns.

We found very short duration bursts (*gusts*) are confined by the existing channel and weaken rapidly. A *gust* may have a significant effect on the pressure of the stand-off shock but does not greatly alter shock locations. A short *blast* temporarily alters the pattern of shocks. After a period in which after-shocks occur, the jet returns to its initial shock structure. Significant pressure increases occur in sequence as the *blast* propagates coherently through and around further standing-shocks downstream. The intermediate duration *prolonged-burst* is sufficient for the channel shape to be narrowed and lengthened, affecting several standing shocks simultaneously. As the burst ends, the channel splits into two sections, one returning to the original form and the second moving to the next standing-shock. A long *sustained-burst* is similar to the *prolonged-burst* affecting multiple standing shocks for a longer period. In each case, a rarefaction wave accompanies the rear of the burst which helps restore the pre-burst jet flow (e.g. see right panel of Fig. 7).

Overall, there is a travelling pressure wave associated with a velocity burst and an increase in standing-shock pressure as the burst transits. These characteristics, which would translate into increased luminosities, are similar to the travelling luminosity knots observed in AGN jets (e.g. M. Lister et al. 2018b). Here, we note that we have made limited essential assumptions in order to approach the fundamental non-relativistic hydrodynamics without regard to particular applied physics and gas dynamics. Correlation with observations will require a conversion of these physical parameters into emissivities, as well as additional physics.

4.2 Low overpressure burst shock propagation and shock diamond interactions

Almost immediately a *blast* enters a jet, a reverse shock forms which generates a region of high pressure and density. However, the expected advancing shock into the slower moving jet gas ahead promptly disappears. This is a consequence of the overpressure which has caused the gas to expand and accelerate. This is illustrated in the top two panels of Fig. 10. The jet expansion, led by the burst through the so-called Zone of Silence, raises the density and velocity, increasing the ram pressure considerably. The bottom panel of Fig. 10 illustrates the large increase in the jet core pressure as the travelling shock interacts with the stand-off shock. This would correspond to an approximate several-fold increase in luminosity. Increases are also observed in standing-knot luminosities as travelling luminosity knots interact with AGN jet standing luminosity knots (e.g. M. Lister et al. 2018b).

We note the following for the low density ratio, low overpressure, fiducial jet M2K2E0.1R10B0.5V1.4, and associated simulations, where burst duration and/or amplitudes are varied further:

1. The bursts do not permanently disrupt the internal jet structure, in the near-field region simulated (bottom panel of Fig. 9). Therefore, one cannot deduce the past jet history directly. However, the far field of the jet may contain a useful record of the history of sustained bursts. In addition, the energy deposited into the ambient medium in the form of ripples, bows and vortices, which are slow to disperse, are potential diagnostics (e.g. Fig. 6).

2. The shock–shock interaction, when the burst crosses an oblique shock-diamond, results in a large temporary increase in jet pressure (bottom panel of Fig. 10).

3. There is a temporary broadening of the jet diameter locally, by about 1Rjet, and high pressure concentric reverse cone shells established, as the burst is forced against and through the dense shock front (e.g. see Fig. 3). For the high jet/ambient density ratio jet, a single thick reverse pressure cone shell is produced (Fig. 14).

4. An increase in radiation would be expected from post-shock jet acceleration, from the energized standing-shock (G. F. Paraschos 2025).

5. The pressure at the jet annulus in the fiducial jet temporarily increases as the burst is forced through and around the standing shock (Fig. 3 and left panel of Fig. 4). The temporary increase in jet annular pressure by about 80 per cent could result in an associated roughly three-fold increase in luminosity.

6. The jet diameter reduces as the burst completes traversing a shock-diamond before it impinges on the next standing shock-front (Fig. 3, centre panel).

7. The burst duration is increased as it passes through a shock-diamond (Fig. 7 right panel). The shock-shock interaction greatly increases jet pressure, by about a factor of 2, and therefore density, which slows the following burst section. With each successive shock–shock interaction, the burst duration becomes extended, being $4t_u$ after crossing four standing-shocks, and burst energy reduces (left panel of Fig. 11). This results in e.g. successively reduced shock-front displacement along the jet axis, with associated reduced magnitude of standing-shock pressure increases. This suggests that eventually, depending upon initial burst energy, the burst may dissipate before reaching the end of the jet.

8. The jet begins to settle back down towards its pre-burst configuration (at $\sim 86 t_u$, Fig. 7 right panel). However, there then follows a delayed, but significant disturbance, which is believed to be caused by the slower Kelvin–Helmholtz jet surface wave associated with the velocity burst. This appears to result in temporary small Mach discs, which rapidly cause internal jet-core shock structure disturbances down-stream (Fig. 8).

9. A shorter duration burst, a *gust*, produces similar effects but with much less energy, as expected (right panel of Fig. 11).

10. A *prolonged-burst* results in multiple standing-shocks being similarly affected at the same time, albeit at different stages of shock–shock interaction. Standing-shock axial displacement is larger than for a shorter duration *blast-burst* (Table 5). Each experiences associated high pressure concentric reverse cone shells (left panel of Fig. 12). Since such an intermediate duration burst simultaneously affects all standing shocks across the computational grid, the long duration bursts, *sustained-bursts*, having similar results, are not reported here, but are available on Zenodo (<https://doi.org/10.5281/zenodo.14579827>).

11. The higher velocity burst produced similar but higher energy effects, with a larger temporary increase in jet radius (Table 4), and greater temporary shock front displacement along the jet axis.

12. A burst causes a pressure shell to expand away from the jet surface (e.g. Fig. 6). This results in a lateral energy burst, a sound wave or pressure ripple, about 10 per cent above ambient pressure, with possible subsidiary ripples, which travel into the surrounding ambient medium. It would appear that a single burst would not be effective at heating the CGM, which would require a continuous series of bursts or pulses (C. J. Bambi & C. S. Reynolds 2019; C. Richards & M. D. Smith 2024).

4.3 High overpressure burst shock propagation and mach disc interactions

The burst simulations for the low density ratio, high overpressure, fiducial burst jet, designated M2K8E0.1R10B0.5V1.4, together with other burst variations, showed that;

1. The burst does not permanently disrupt the internal jet structure of these highly energetic jets, in the near-field, which have a dominant stand-off Mach disc (top left and top right panels of Fig. 16)
2. The shock–shock interaction results in a temporary increase in pressure (and therefore luminosity), a broadening of the jet locally, and high pressure concentric reverse cone shells, similar to the low-pressure jet, as the burst is forced against the dense strong shock front (Fig. 17).
3. An unquantified temporary increase in radiation upstream of the standing-shock front would also be expected, as a result of increased particle acceleration from the high pressure shock–shock interaction (G. F. Parashos 2025).
4. The pressure at the jet annulus temporarily increases as the burst is forced through and around the strong standing shock, temporarily displacing it. The displacement along the jet axis is about twice that of low overpressure jets (Table 5 and right panels of Fig. 16). For these higher overpressure jets, the strong Mach disc means that a burst cannot pass through the shock front as readily as a weak oblique regular reflection standing-shock. However, it does mean that the shock fronts undergo much larger transient displacements in jet axial position, and can temporarily shrink Mach disc size (3rd and 4th panels of Fig. 17).
5. The high overpressure jets are disturbed post-burst, but begin to settle back down very quickly compared to the low overpressure jets, i.e. with much reduced residual post-burst energy disturbances (e.g. see Fig. 16) compared to the low overpressure jets.
6. Shorter duration bursts produce similar effects but with much less energy. Longer duration bursts result in a longer Mach disc displacement (Fig. 16).
7. The burst leads to a expanding pressure shell and lateral energy burst, e.g. for an intermediate duration burst the single sound wave pressure ripple is just visible in the turbulent ambient of the simulations (e.g. see Fig. 17).
8. High overpressure heavy jets produce a single, thick, temporary high pressure reverse cone shell during the shock–shock interaction (Fig. 14, and right panel of Fig. 18).
9. The higher velocity burst in a heavy jet (M2K8E10R10B4V3) produced similar but higher energy effects, as expected, e.g. greater temporary Mach disc displacement (16Rjet) (e.g. Figs 18 and 19).

4.4 Potential observational diagnostics

The objective of our limited purely hydrodynamic simulations was to understand the fundamental physics of shock–shock interactions via a systematic survey of parameter space for Mach 2 jets, and identify any potential observational diagnostics worth developing further. For example, our results establish the significance of burst duration in determining shock behaviour. However, any one-to-one correlations with real AGN jets would require significant additional simulation physics. Where for example adding specific magnetic fields may be expected to generally add stability and constrain jet boundaries (Y. Mizuno et al. 2016), and specific

relativistic flows to enhance shock strengths and change timing and energy scales (J.-M. Martí 2019; D. C. Homan et al. 2021).

Overall, there was a travelling pressure wave associated with a velocity burst, and an increase in standing-shock pressure as the burst transits. These characteristics, which would translate into increased luminosities, are generally similar to the travelling luminosity knots observed in AGN jets (e.g. M. Lister et al. 2018b). One specific example is observations of relativistic Blazar CTA 102 between 2016 and 2018 which indicated a shock-shock interaction between a travelling shock and a quasi-stationary standing shock, between 2 and 17 pc from the SMBH, resulting in a four-fold increase in the standing-shock flux density, with a rise-time of <250 d (e.g. S. Kim et al. 2025). The increase in luminosity, at least, is of the same order as our fiducial jet which indicated a transient increase in standing-shock pressure corresponding to a three-fold increase in luminosity (e.g. Section 3.2 and Fig. 10).

We also identified e.g. greater standing-shock axial displacement for higher overpressure jets, larger changes to jet diameter for longer duration bursts, and post-burst jet disturbances for low overpressure jets. Potentially, observational diagnostics could also be developed e.g. using detailed systematic simulations for various overpressures, density ratios, and Mach numbers, to derive empirical luminosity variations versus jet–velocity relationships. We note that a general prediction when a burst is released into an overpressured jet is the delay time between the outbursting source and the burst overtaking the stand-off shock. However, there will be some uncertainty over the stand-off distance from the nozzle, which will be some distance from the central SMBH (Y. Y. Kovalev et al. 2020b).

5 CONCLUSIONS

We have used the fluid dynamics code PLUTO in a 2D axisymmetric purely hydrodynamic configuration, in order to initially understand the fundamental physics of the effect of a velocity burst travelling along low Mach, Mach 2, overpressure jets. This was prompted by observations of travelling luminosity knots in AGN jets, which are complex, with e.g. relativistic flows and magnetic fields, and which are little understood. For example, such bursts or flares may be caused by a temporary step increase in the accretion rate of the central super massive black hole. We were particularly interested in the interaction between a travelling-shock and a standing-shock, and explore the potential for any observational diagnostics which could be developed to reveal jet physics indirectly.

A systematic survey of parameter phase-space was carried out. This involved four different constant inflow base-jets, with a velocity burst superimposed, utilising various configurations. The main bursts consisted of short, intermediate, and long burst durations relative to the associated jet dynamics, plus also two velocity amplitudes. Of the combination of 24 burst jet configurations, two of interest were studied in more detail to examine shock-shock interactions. Both jets had low jet/ambient density ratios.

Summary of Key findings;

1. There are large increases in jet pressure, corresponding to a several-fold increase in luminosity in the jets examined, as a pressure burst transits a standing-shock. An increase in other radiation from the standing-shock front would also be expected.
2. Each shock–shock interaction results in a standing shock being temporarily translated further along the jet axis, particularly so for high overpressure jets.

3. For both low and high overpressure jets, high pressure concentric reverse cone shells are temporarily established, and jet diameter also increases locally, as the burst transits through and around a dense standing-shock.

4. A velocity burst does not permanently alter internal jet shock structures in the near-field, with a post-burst rarefaction wave helping re-establish pre-burst jet dynamics.

5. A burst does lead to a single main lateral ambient pressure wave, which is not significant regarding heating the CGM.

6. In low overpressure jets, the burst duration increases incrementally as it passes successive standing shocks.

7. There are residual energy disturbances post-burst which affect internal jet shock structures, and which are more prolonged in low overpressure jets. These may be caused by slower Kelvin–Helmholtz jet surface wave instabilities.

There is the potential to infer jet physics, with the aid of significant additional simulation physics, using observational diagnostics. Interpretation of observations will require a conversion of these physical parameters into emissivities. Further research is planned to repeat this work to determine corresponding approximate luminosity-intensity variations and position–velocity (line of sight) variations, for given sky-angles.

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We thank the referee for helpful comments and suggestions.

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. Underlying 1000-frame movies of a selection of simulations and post-processing simulation output images, graphs etc are available in the Zenodo repository, at <https://zenodo.org/records/14579827> or through <https://doi.org/10.5281/zenodo.14579827>.

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