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Investigation of jet formation from the blast wave of a locally heated laser-irradiated target

H. Schmitz*, A.P.L. Robinson

Central Laser Facility, STFC, Rutherford Appleton Laboratory, Didcot, Oxon., OX11 0QX, UK

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ABSTRACT

A possible mechanism responsible for the formation of jets observed near young stellar objects is thought to involve conically converging flows which are generated when the stellar wind encounters an inward facing shock at an oblique angle. While this mechanism of inertial collimation has been verified by simulations, it is not accessible to direct observations due to the small scales on which it operates. Until recently, laboratory experiments have only been able to reproduce the second part of the mechanism by directly creating a converging conical flow to produce a jet. In this contribution we present a conceptual numerical study proposing an new configuration to create jets that are able to reproduce both stages of the mechanism, including the inward facing reverse shock, from simple initial conditions. By selectively heating a small region inside a target, irradiated by a high-intensity laser pulse, a jet can be created inside the plasma behind the rear target surface. We present three dimensional simulations of the formation of the jet. We find jets with aspect ratios of over 15 and Mach numbers between 2.5 and 4.3. The influence of simulation parameters is investigated and the applicability of the jets to their astrophysical counterparts is discussed.

1. Introduction

Astrophysical jets have been the subject of investigation for many years. They occur on a large range of different scales, ranging from the up to megaparsec scale jets of active galactic nuclei (AGNs) [1] to the sub-parsec scale of jets produced by young stellar objects (YSOs) [2,3]. Observations show that the jets can have large aspect ratios and remain collimated over long distances. While the flow in AGN jets is highly relativistic, jets observed in YSOs and protoplanetary nebulae (PPNs) typically has velocities of ~100 km s^{-1}. It is thought that YSO jets could be generated by conical converging flows. According to the model by Canto [4,5] the stellar wind encounters an stationary, inward facing, oblique shock that focuses the flow towards the axis. Near the axis the outflow is shocked again and forms a thin jet travelling radially outward. A schematic diagram of this inertial collimation mechanism is shown in Fig. 1. Simulations of the second step of this mechanism showed that a jet could be formed by a conically converging flow [6]. In subsequent simulations the mechanism was shown to be effective when the stellar wind interacts with a toroidal circumstellar environment [7]. Observations indicate that this mechanism could also be at work in the protoplanetary nebula HE 3-1475 [8]. In this object a conical dense structure is observed that ends at the location of a bright emitting region in the jet. An alternative to inertial collimation is magnetic collimation. While this is believed by some authors to be the dominant mechanism for YSO jets [9], evidence for this is not conclusive.

At larger distances from the central object many jets exhibit several bright regions, known as knots, along the path of the outflow. Some argue that, in the case of YSO jets, these knots originate from variability of the jet outflow velocity at the source ([10] and references therein). At least for AGN jets these knots, however, originate from internal oblique recollimation shocks in the jet flow [11]. These shocks are formed when the jet flow extends into regions where the ambient pressure drops with distance from the central object. When the ambient pressure changes the jet is not in pressure equilibrium with its surroundings. In order for a new equilibrium to be reached the jet must expand radially, therefore reducing the pressure inside the jet. For small pressure differences the jet can adjust to the new environment without forming shocks [12] and forms standing oscillations around the equilibrium radius. If the density decays faster than R^{-2} then the jet

* Corresponding author.
E-mail address: holger.schmitz@stfc.ac.uk (H. Schmitz).

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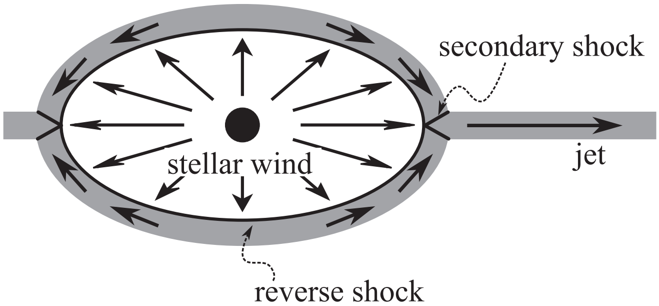

Fig. 1. Schematic of the jet formation mechanism proposed by Canto [4,5]. The stellar wind obliquely hits the reverse shock and focuses. After converging on axis, and being redirected by the secondary shock, a jet forms.

expands freely with a constant opening angle [13]. This corresponds to the expansion of jets into a vacuum. If, on the other hand, the density decays slower than R^{-2} but fast enough to prevent the jet to adjust gradually, the jet flow will expand into the lower density region but will, due to inertia, become underdense before it contracts again and forms standing recollimation shocks.

Observations of astrophysical jets can only provide indirect evidence of the underlying physical processes. The limited spatial resolution makes it impossible to resolve the microphysics inside the jet or the source of the jet. Also, due to the large time scales on which the processes take place, only snapshots can be observed. Simulations can support observations and allow us to analyse small scales and longer time scales. However, simulation codes often describe only a simplified model and need to be verified against measurements.

In recent years, laboratory experiments have opened up a new possibility to study astrophysical jet flows. In early experiments, in which material was ablated from a solid plane target by a high intensity laser pulse, jet formation was observed [14]. Later experiments showed that the formation of a jet under these conditions is not due to a magnetic field but is determined by radiative cooling [15]. Other experiments were performed to produce jets by converging flows. Using laser driven ablation from a conical target it was found that the amount of energy loss due to radiation had direct influence on the radius of the jet [16,17]. This result had already been predicted by simulations which investigated a similar configuration [18]. A similar dependence on radiative cooling was found in jets produced in conical wire Z-pinch experiments [19]. Ciardi et al. [20] recently created a jet that was formed by a fast flow inside a cavity interacting with a dense shock envelope. The flow resembled the Canto model but the collimation was achieved only by applying a strong axial magnetic field.

A common feature of all the laser based experiments presented above is that the jet travels into a vacuum. Astrophysical jets commonly expand into an ambient medium which strongly influences the shape and evolution of the jet. In order to simulate the ambient medium in laboratory experiments using lasers, the jet is made to expand into a low density foam [21–24]. In these experiments a foil or plug acts as a pusher which is mounted in front of a hole through a washer. The laser ablates some material from the pusher which creates a shock in the remaining pusher material leading to an expansion through the hole. The cylindrical hole collimates the flow which then forms a jet behind the rear target surface. A low density foam mounted on the rear target surface acts as the ambient medium into which the jet expands. An experiment in which the jet interacted with an obstacle embedded in the foam was presented by Hartigan et al. [25]. In a recent experiment by Yurchak et al. [26] inertial collimation was achieved by creating a second, ring shaped outflow from the target. This created a cavity confining the central outflow and forcing it through a narrow channel. A comparison of the different methods of creating astrophysical jets with lasers in the laboratory can be found in Ref. [27].

In recent years it was found that resistivity gradients in solid density targets can effectively control the flow of fast electrons within the target [28]. Fast electrons are generated by the ponderomotive force of a high intensity laser, interacting with the critical density surface near the front of the target. Structuring the target, using materials of different Z, allows to confine the fast electrons within the high-Z material [29,30]. The flow of the return current, which neutralises the fast electron flow, results in localised Ohmic heating of the target. The geometry of the high-Z material and the parameters of the laser can give control over the region heated in this way. For some configurations the heated region can be reduced in size to the order of 10 μm [31]. A short laser pulse results in rapid heating of the target, compared to hydrodynamical timescales. This makes the rapid heating by resistively guided fast electrons an ideal driver for shocks in the solid density target which can be studied in their own right, or which can be used to drive jets into an ambient medium behind the target.

In this paper we propose a new mechanism for generating astrophysically relevant jets by selectively heating a small high-Z region within a solid density target. In section 2 we describe the simulation code and the geometry and parameters of the setup. The geometry of the initial conditions is quite simple, consisting of a heated disk embedded in the target and small conical crater on the rear surface. The jet forms naturally from the interaction of the blast wave with the shaped rear surface of the target. There is no need to artificially restrict the flow imposing strong magnetic fields or external flows. We point out that, in the context of this work, we do not include the electron transport or the Ohmic heating by the return current in our simulations. Instead, we assume that the fast electrons can be controlled by resistive guiding to deposit energy in a localised region inside the target. Our simulations start with a prescribed temperature profile. In section 3 we describe the results of the simulations for different parameters and in section 4 we discuss the implications of the results in an astrophysical context. A summary is given in section 5.

2. Simulation setup

We use a newly developed 3 dimensional MHD code to simulate the expansion of a heated region inside a solid target into vacuum. The code is based on the central-upwind scheme of Kurganov [32], combined with the constrained transport technique [33]. The method has been extended to include different temperatures for ions and electrons as well an arbitrary number of ion species.

The code numerically approximates the following set of equations

$$\partial_t \rho_k + \nabla \cdot (\rho_k \mathbf{v}) = 0 \qquad (1)$$

$$\partial_t (\rho \mathbf{v}) + \nabla \cdot \left[\rho \mathbf{v}\mathbf{v} + \left(p + \frac{|\mathbf{B}|^2}{2\mu_0} \right) \mathbf{1} - \frac{1}{\mu_0} \mathbf{B}\mathbf{B} \right] = 0 \qquad (2)$$

$$\partial_t e + \nabla \cdot \left[\left(e + p + \frac{|\mathbf{B}|^2}{2\mu_0} \right) \mathbf{v} - \frac{1}{\mu_0} (\mathbf{v} \cdot \mathbf{B}) \mathbf{B} - \mathbf{q}_e \right] = 0 \qquad (3)$$

$$\partial_t r + \mathbf{v} \cdot \nabla r + \frac{1}{\varepsilon} (1 - r) \nabla \cdot \mathbf{q}_e = \frac{Q_{ei}}{\varepsilon} \qquad (4)$$

$$\partial_t \mathbf{B} + \nabla \times \mathbf{E} = 0 \qquad (5)$$

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