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Experiments to investigate the effects of radiative cooling on plasma jet collimation

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ABSTRACT

Preliminary experiments have been performed to investigate the effects of radiative cooling on plasma jets. Thin (3 μm–5 μm) conical shells were irradiated with an intense laser, driving jets with velocities >100 km s^{-1}. Through the use of different targets materials – aluminium, copper and gold – the degree of radiative losses was altered, and their importance for jet collimation investigated. A number of temporally-resolved optical diagnostics was used, providing information about the jet evolution. Gold jets were seen to be narrower than those from copper targets, while aluminium targets produced the least collimated flows.

1. Introduction

Jets from young stellar objects (YSOs) are associated with the accretion phase of stellar evolution, which lasts for approximately the first 10^5 years of a young star's life, see Reipurth and Bally [1] for a review. The jets are seen propagating away from the star at speeds of the order of 500 km s^{-1}, with lengths of up to 1 pc, and with aspect ratios (jet length/jet width) of 10 or more. The flows are often seen to terminate in regions of optical emission, and contain a series of bright knots known as Herbig–Haro (HH) objects. The relatively close proximity of these systems means that observations of radiation from HH objects are details, and has allowed a large amount of high-quality observational data to be collected. These objects have dynamic time-scales of the order of a decade, and it is thus possible to observe the jet as it evolves. YSO jets act as cosmic laboratories to test our models of compressive magneto-radiative-hydrodynamic flows, and these data, along with theoretical and computational modelling, have lead to significant improvements in understanding. Despite this, questions still exist surrounding the physics of both the jet launching and propagation, and so performing well-designed laboratory simulations that advance our knowledge has potentially large benefits. This experiment represents part of an ongoing campaign [2–5] to aid in the understanding of aspects of jet propagation physics, and in particular the high degree of collimation over very large distances. There are three main physical processes which are thought to be important: 1/inertial confinement of the flow by the ambient medium, 2/radiative cooling of the jet, causing a drop in the internal thermal pressure and a collapse on axis, and 3/magnetic fields which act to restrict the radial expansion of the charged particles. A number of experiments have taken place in recent years to investigate jet propagation. These have demonstrated the propagation of a jet moving into an ambient medium, either stationary [6–8] or in the form of a plasma crosswind [9], and an increase in jet collimation due to radiative cooling [10–13]. The work presented here shows an experimental scheme aimed at studying the effects of radiative losses on the collimation of plasma jets. Conical targets are irradiated with an intense laser, in a similar scheme to that used by

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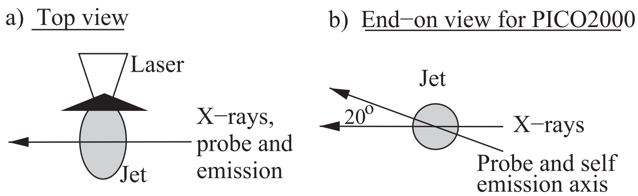

Fig. 1. The experimental set-up. Panel a) shows the orientation of the optical probe and self-emission diagnostics used in both experiments, as well as the X-ray radiography used only in the PICO2000 experiment. The angular separation between the optical and X-ray axes used in the PICO2000 experiment is shown in panel b). This configuration allowed both diagnostics to be used simultaneously. In this view the jet is propagating out of the page.

Nikitin et al. [14], resulting in jets of high velocity. By choosing different targets materials – here gold, copper and aluminium – the importance of radiative losses can be altered, since higher atomic number materials radiate more efficiently. This radiation cools the jets on axis, and lowers the thermal pressure driving the radial expansion. As a result, more radiative jets are expected to have larger aspect ratio and to be more collimated. Results are given from two experimental campaigns, the first at the GEKKO XII, 12 beam, 10 kJ, Nd:glass laser system at the Institute for Laser Engineering, Japan. The second experiment took place at the PICO2000 facility at the Ecole Polytechnique, France, which combines a 100 J, picosecond, Nd:glass laser with a 1 kJ, nanosecond, Nd:glass laser.

2. Experimental design

The primary experimental configuration is shown in Fig. 1. Five beams of the GEKKO XII laser irradiated the apex of the conical shell, delivering 500 J of laser light in a 500 ps pulse, at a wavelength of 351 nm. The focal spot size diameter was 600 μm. The plasma from the rear face of the target is focused on axis due to the conical geometry, and forms a jet. A second, mJ, 527 nm, 20 ns laser pulse probed the system in the direction perpendicular to the plasma flow. The delay between the arrival of the probe beam and the drive lasers was varied up to a maximum of 70 ns. A modified Nomarski interferometer analysed the beam, and was detected with a gated optical imager (GOI) with a temporal resolution of 250 ps. In addition, the self emission from the jet at a wavelength of 450 nm ±10 nm was collected and imaged onto two more GOIs, both with a 1.5 ns gate width, and a streak camera with a 28 ns time window. The cone targets were made from either 5 μm thick gold, 5 μm thick copper, or 3 μm thick aluminium. All the targets had a full opening angle of 140° and a diameter of around 1.2 mm.

A second experiment took place at the PICO2000 facility. In this case only copper targets were used, and were irradiated with ~400 J, 1 ns, 532 nm laser pulses, focused through hybrid phase plates to give a 400 μm diameter focal spot. A mJ, 527 nm, 8 ns laser was again used to probe in the direction perpendicular to the jet propagation axis, and was detected with a GOI with a time resolution of 120 ps. Here, no interferometer was used, and the diagnostic was used in a shadowgraphy configuration. A streak camera, with a time window of 50 ns, recorded the self-emission at 450 nm ±10 nm transverse to the jet propagation direction. An additional X-ray radiography diagnostic was implemented for this experiment. Laser pulses of 60 J, 30 ps at 1064 nm, and a focal spot of 50 μm, irradiated a Ti foil placed 20 mm away from the conical shell. The resulting Ti-kα emission at 4.75 keV was used to radiograph the jets at varying times during their evolution, using imaging plate as the detector. The axis of the x-ray and optical diagnostics were separated by 22°, allowing both diagnostics to be used simultaneously.

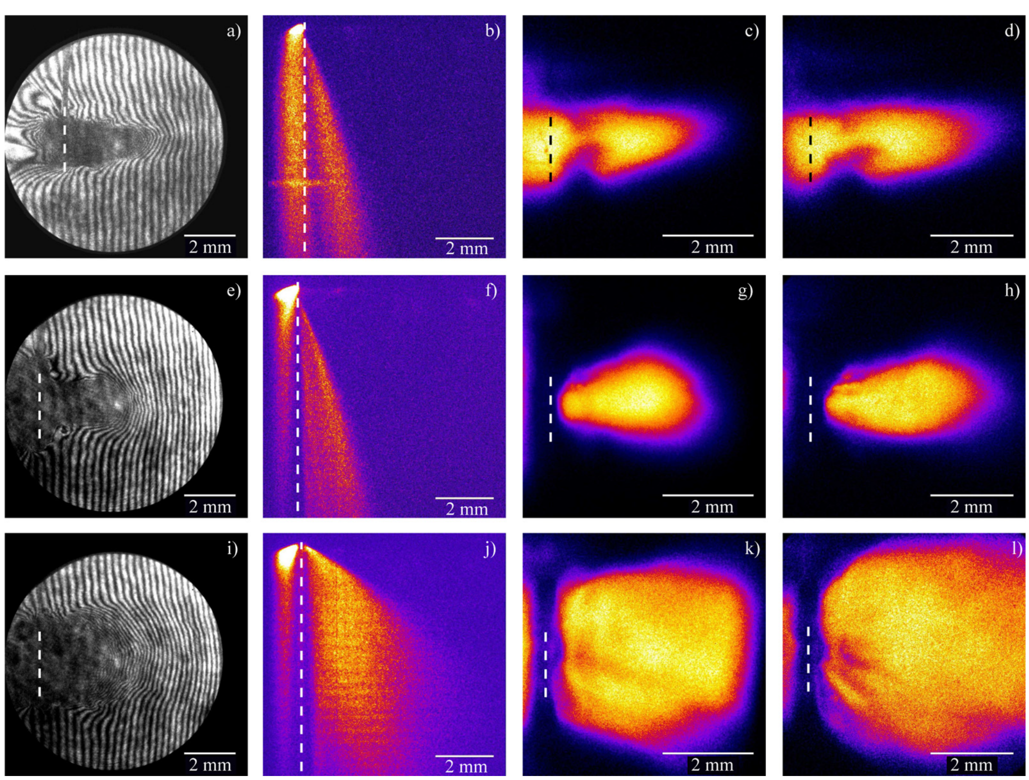

Fig. 2. The data from the optical diagnostics used in the GEKKO XII experiment. The top, middle and bottom rows represent data for gold, copper, and aluminium targets respectively. The columns, from left to right, show data from the interferometry with a probe delay of 50 ns, the streaked self-emission over the first 28 ns of the jet evolution, the imaged self-emission after 50 ns, and the imaged self-emission after 70 ns. The dashed line indicates the initial target location on the horizontal axis. See text for further details.