Laboratory Experiments to Study Astrophysical Shock and Jets

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Abstract. We describe laboratory laser-plasma experiments to form plasma jets and study jet driven shocks in an ambient gas. Particular questions that are of interest are the formation and collimation of these jets, and the relevance of experiment to astrophysical jets and shock waves. Our objective is to develop an experimental analogue to non-relativistic jets associated with Young Stellar Object. The experiments were performed with Gekko XII HIPER laser system at the Institute of Laser Engineering. Four types of targets were explored, these used flat, and hemispherical CH shell attached to a gold guide cone, a low-density foam-filled cone and stagnation plasma from an imploding hemisphere CH shell. To study jet driven shocks, a helium gas jet was used to form a low-density background gas at the rear, jet forming, surface of the target. The plasma jet and shock were measured with a Mach-Zender interferometry diagnostic, and rear-surface self-emission diagnostics. These diagnostics enable the jet shape, electron density and temperature to be inferred. All the four types of the targets produced clear jets.

1. Introduction

During the accretion phase of star formation, huge jets of material are observed moving away from the compact central object. These Young Stellar Object (YSO) jets remain collimated over length scales \( > 10^{18} \) cm, and can terminate in regions of optical emission known as Herbig-Haro (HH) objects. The jet shocking against the surrounding interstellar medium causes HH objects. Due to their relative proximity to earth, the short evolutionary time scales and radiative nature, many of the physical properties of these YSO jets are well constrained by observation. The underlying physics that generates and collimates these jets is not understood.

In this paper we describe an experiment that uses laser-produced plasmas to study connected to the formation and collimation of plasma jets and jet launched shock waves. A particular motivation is to scale our experiments to the non-relativistic jets associated with YSOs. Recently, supersonic-jet experiments have been conducted using high-power lasers, and the dimensionless quantities such as Mach number (\( M \)), Reynolds (\( Re \)) and Peclet (\( Pe \)) numbers have been compared with YSO jets [1].

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2. Experimental
The experiments were performed on Gekko XII HIPER laser at the Institute of Laser Engineering (ILE), Osaka University. This a 12-beam Nd: Glass laser. Nine of the beams are converted to 3rd harmonic, wavelength $\lambda = 352$ nm, delivering 75 – 95 J in a beam to target in a 500 ps duration pulse. Figure 1 is a top view of a schematic of the experimental setup. Jet formation from four types of targets was studied. These targets are; (a) a 10 $\mu$m thick plane CH foil coupled to a gold cone (inset in Fig. 2), (b) a 600 $\mu$m diameter, 10 $\mu$m thick hemisphere CH shell coupled to a gold cone, (c) a low-density foam-filled cone [2], and (d) a 10 $\mu$m thick hemisphere CH shell. We label these targets P-cone, HS-cone, F-cone and HS respectively. The beam focusing was different for the targets. The P-, HS- and F-cone targets were irradiated with a 4-beam bundled laser and focal spot diameter of $\sim 300$ $\mu$m without KPP plates [3]. The laser intensity $I_L$ was $\sim 10^{15}$ W/cm$^2$. For the HS targets, 5 beams without KPP plates were irradiated onto the target at the position of the apices of a regular pentagon with the length of a side $\sim 470$ $\mu$m. The laser intensity in each 5 focal spots was $\sim 2 \times 10^{14}$ W/cm$^2$. The HS targets were used to investigate the convergence of 5 plasmas from the interior of the hemisphere onto the common axis and the collimation of the stagnating plasma.

To simulate the environment surrounding astronomical jets, which can result in jet collimation and shocks, a large-diameter (10 mm) gas jet system was placed beneath the target at the bottom on the vacuum chamber. The gas jet, with a back-pressure of 50 atmospheres, is timed to produce a uniform He gas environment on the rear surface of the target with a gas particle density of $\sim 5 \times 10^{17}$ cm$^{-3}$. The interaction between the supersonic plasma jet and the gas results in a shock.

The plasma jet and shock were measured with a Mach-Zender interferometry diagnostic, using a frequency doubled pulsed Nd: YAG laser, $\lambda = 532$ nm and pulse duration of 10 ns. The probe axis was transverse to the jet propagation direction as shown in Fig. 1, and the beam split in to a gated ICCD camera to provide 2-D images and a streak camera to a 1-D image for 8 ns. Time resolution is provided by a synchronized and time-delayed gated ICCD camera, with 200 ps resolution, and a S1 streak camera with time resolution of 50 ps. A series of filters, a high-pass filter ($\lambda > 370$ nm), a low-pass filter ($\lambda < 800$ nm), two interference filters ($\lambda = 532$ nm, $\Delta\lambda = 2$ nm), and a Super Notch Plus filter (cut $\lambda = 527$ nm with $\Delta\lambda = 4$ nm), were used to improve the signal to background ratio and eliminate scatter from the harmonics of HIPER laser at wavelengths of 352, 527, and 1054 nm. A High-Speed Sampling Camera (HISAC) [4] and Streaked Optical Pyrometer (SOP) [5] were used to obtain time-evolution measurements of 2-D self-emission profile and temperature, respectively, for the rear-side of the targets. The target chamber
vacuum port geometry limited the angle of view to 30° degrees from rear-side target normal direction. The diagnostics imaged the emission through a blue interference filter ($\lambda = 450$ nm, $\Delta \lambda = 10$ nm).

3. Results

In all the four types of the targets, clear jets were observed with the transverse ICCD and streak camera diagnostics. The principle measurements were taken using the interferometry ICCD and streak camera diagnostics; a reference interferometry measurement was taken immediately before each target shot. This enables the reliable extraction of phase information from the images and by implementing an Abel-inversion routine an estimate of the 3-D electron density. In Fig. 2, we show a raw data 2-D image of the transverse interferometry of the P-cone target measured with the ICCD camera at 1.37 ns after the HIPER laser. We see that a clear plasma jet is produced. The insert illustrates the geometry, position, and orientation of the P-cone target.

Figure 3 illustrates the orientation of, and data taken from, the streak cameras. The schematic in Fig. 3(a) shows the P-cone target on the right, and an artist’s impression of a jet leaving the cone. The black rectangle indicates the position of the streak camera slit. The data in Fig. 3(b) is the static image, and in Fig. 3(c) is a streak image of the transverse-interferometry measurement. These measurements are taken from the same experimental shot as shown in Fig. 2. Shifts in fringes in Fig. 3(c) result from plasma at the front edge of the jet. This measurement indicates that jet velocity, derived from the evolution of the fringe shifts, see the solid line in Fig. 3(c), was $(4.8 \pm 0.3) \times 10^5$ m/s. In comparison, Fig. 4 shows a streak image of the transverse interferometry for the SH-cone target. Here the inferred jet velocity was $(3.8 \pm 0.4) \times 10^5$ m/s. We note that delay from the irradiation of HIPER laser to the appearance of the jet is longer for the SH-cone target compared with that for the P-cone target, this is consistent with the longer distance from the laser spot to the exit hole of the cone and the measured lower jet velocity for the SH-cone target.

Typical jet velocities for the F-cone target with $I_L \sim 10^{15}$ W/cm$^2$ and HS target were $(3.2 \pm 0.6) \times 10^5$ m/s and $(1.5 \pm 0.3) \times 10^5$ m/s, respectively. Among the four types of targets, P-cone and SH-cone targets represented the largest jet velocity.
jet velocity for HS-target is probably due to the lower laser intensity, roughly 1/4 of other targets. Images from HISAC for a HS target are shown in Fig. 5. This data shows the on axis plasma stagnation and heating as plasma from the 5 focal spots collide. Red dots represent the position of the target chamber center. Time $t_0$ is not calibrated in this measurement. There is some evidence of plasma disassembly following the collision. Detailed analysis of this data and shock-like structure observed ahead of the jets in the He gas is in progress.

4. Summary and Conclusions
Using the Gekko XII HIPER laser system we have investigated laboratory laser-plasma experiments to address questions connected to the formation and collimation of plasma jets and jet driven shock waves. In all the four types of the targets, jets were clearly observed in the transverse ICCD and streak measurements. The primary motivation is a study of the plasma dynamics that can result in extended plasma collimation, investigate four different target geometries. Data analysis will continue to derive jet temperatures and densities, and we plan to extract scaling parameters or dimensionless quantities ($M, Re, Pe$ etc.) from these measurements and explore the relevance of each of these experiments to non-relativistic jets associated with Young Stellar Object.

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