Laboratory plasma astrophysics simulation experiments using lasers

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Abstract. Laboratory astro-plasma physics experiments are being designed to advance both our astrophysics and plasma physics knowledge. With current high-energy and high-power laser technology, it is possible to reproduce the conditions of temperature and pressure met in extreme stellar environments in the laboratory. Coupled with sophisticated target design, laboratory simulation of aspects of astrophysical phenomena are in progress. The focus is to design experiments that address key aspects of the plasma physics occurring in astrophysical objects such as a supernova remnant or jet. This approach uses a plasma physics model, typically ideal MHD, to define a set of scaling criteria. Laboratory experiments are tested against this set of criteria. It is often the case that neither the astrophysical object nor the experiment achieves the constraints demanded by a model such as ideal MHD. Outlined are experimental approaches to dealing with less rigorous scaling and results from scaled experiments designed to address aspects of the shocks in a young supernova remnant and collimation of jets associated with protostellar objects.

The goal of laboratory astroplasma experiments is the exploration of fundamental physical processes - and, importantly, combinations thereof - in a controlled environment [1]. The spring board for this undertaking are the many wonderful and often perplexing observations of astrophysical phenomena. Phenomena include the seeding and acceleration of cosmic ray in collisionless shocks and the production and collimation of plasma jets. The difference in length and temporal scales between astrophysical plasmas and those produced in the laboratory is striking and challenging. Astrophysical plasma often have a hydrodynamic length scale, $L_H$, that is large. The result is that on the scale $L_H$ the viscosity, and thermal conduction and so forth are small, thus dimensionless numbers which determine the ratio of advection to viscosity, the Reynolds number $Re$, and convention to conduction, the Péclet number $Pe$, are very large. This greatly simplifies the hydrodynamic or magnetohydrodynamic equations that apply and can allow rigorous scaling across many orders-of-magnitude, i.e. from the astronomical scale to the laboratory scale. The physical models that allow scaled laboratory experiments are ideal hydrodynamics [2] as described by the Euler equations and ideal magneto-hydrodynamics. In the laboratory $L_H$ is small, say order 1 mm, high densities are needed to reduce viscosity, conduction etc and achieve large $Re$ and $Pe$ and ensure that these ideal models are valid.

Additional constraints apply to experiments, these are matching the Euler number, the ratio of a characteristic flow speed to a characteristic sound speed, and the plasma $\beta$, the ratio of the plasma
pressure to the magnetic pressure. If these ratios are matched, then the hydrodynamics or magnetohydrodynamics is similar in both plasmas. Finally, if one is interested in the temporal evolution of the plasmas then a shape function and scaled time must be matched in both systems. These are demanding requirements, and necessary for some experiments, however many astronomical plasmas are not ideal.

The shocks associated with young supernova remnants (SNR) are collisionless, at sufficiently large \( L_\parallel \) it is possible to use an effective collisionality and apply ideal MHD. Key physical processes occur on scales defined by the ion Larmor radius; at this scale, ideal MHD and rigorous scaling do not apply. Protostellar jets are examples of plasmas cooled by the emission of radiation, with radiative processes influencing the plasma dynamics. The ideal plasma models and scaling described above does not apply. Laboratory experiments are possible; however, a less rigorous approach is applied. A sufficient condition is to demand that the plasma is hydrodynamic with small viscosity and heat conduction [3].

Furthermore, for an experiment to be of value it is necessary to determine the relevant dimensionless parameters and scaling criteria from measurement. In the experiments described here, particle densities below critical density to optical radiation are used to enable optical time- and space-resolved probing. These techniques include interferometry to infer electron densities, shadowgraphy and schlieren imaging to determine the shape and structures in the plasma, and spectral line widths and Zeeman splitting measurements to give indications of the ion temperature, and magnetic field respectively. At higher densities, such as those achieved in a plasma jet, streaked self-emission optical pyrometry (SOP) gives the electron temperature. With these measurements, it is possible to determine the collisionality, \( Re \) and \( Pe \) numbers, Larmor radii, plasma \( \beta \), Mach numbers and radiative cooling.

A scaling between a SNR shock at approximately 100 years following a supernova explosion and a laser-plasma experiment is shown in Table 1. This scaling assumes ideal-MHD and crosses 20-orders-of-magnitude. In order to achieve ideal MHD behaviour the \( Re, Re_m \) and \( Pe \) numbers must be large. In the laboratory, this is possible by generating low temperature, high density plasmas which have small viscosity, magnetic diffusivity and thermal conduction. These conditions are met in shock driven and exploding thin foils. Generally, shock driven experiments require multi-kilojoule lasers, whilst supersonic explosion of thin foils is feasible using sub-kilojoule lasers. The scaling in Table 1 is for the explosion of a 100 nm thin CH plastic foil irradiated at an intensity of \( 10^{14} \text{ W/cm}^2 \) in a 100 ps duration pulse. The magnetic field is applied using an external electromagnet; with the predicted experimental magnetic Reynolds number, field penetration of 100 \( \mu m \) in 500 ps is anticipated. The magnetic field must result in a Larmor radius smaller than the particle collisional mean-free-paths (mfp) and characteristic length of the experiment. This demands a strong magnetic field, whilst, a large plasma \( \beta \) demands a relatively weak field.

A particular challenge of using laser-produced plasmas is the high particle densities and relatively low temperatures, which result in highly collisional plasmas. Using a colliding plasma scheme and low atomic number materials it is possible generate a collisionless interaction. An outline of the colliding geometry is shown in Figure 1. The high flow speeds of the opposing plasma flow results in particle mfp’s that exceed the experiment size of 1 mm. Furthermore, the plasma ram pressure associated with this flow results in a large plasma \( \beta \) (> 100). At a magnetic field of 7 T, the fields achieved during the experiment, result in ion Larmor radius below the experiment size. The scaling parameters are summarised in Table 2. This indicates that a scaled of snapshot of a collisionless SNR shock at a

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**Table 1.** Generic set of data for a 100 year old SNR compared to a scaled experiment [4].

| Quantity      | SNR                  | Laser exp         |
|---------------|----------------------|-------------------|
| Length, \( L_\parallel \) | \( 3 \times 10^{16} \text{ m} \) | \( 5 \times 10^{13} \text{ m} \) |
| Time          | 100 yrs              | 500 ps            |
| Density       | \( 1 \text{ cm}^{-3} \) | \( 10^{18} \text{ cm}^{-3} \) |
| Speed         | \( 10^8 \text{ cm/s} \) | \( 10^8 \text{ cm/s} \) |
| Magnetic      | \( 10^{-10} \text{ T} \) | \( 2 \text{ T} \) |

**Table 2.** Scaling parameters for SNR at 100 years compared to experiment at 500 ps [4].

| Parameters                  | SNR | Experiment |
|-----------------------------|-----|------------|
| Ion mfp/\( L_\parallel \)   | 2 \( \times 10^6 \) | 300 |
| Ion Larmor radius/\( L_\parallel \) | \( 10^9 \) | 0.1 |
| Reynolds number, \( Re \)   | \( 10^{13} \) | \( 10^7 \) |
| Magnetic Reynolds, \( Re_m \) | \( 10^2 \) | 100 |
| Peclet number, \( Pe \)     | \( 10^{11} \) | \( 10^{10} \) |
| Euler number, \( E_u \)     | 18  | 21         |
| Alfven Mach, \( M_a \)      | 300 | 20         |
| Mach number, \( M \)        | 16  | 12         |
| Beta flow, \( \beta^* \)    | 500 | 400        |
certain time (100 years) after the supernova explosion is possible. The intention is not to create an experiment that looks and evolves like a SNR, the emphasis is on creating conditions similar to those close to a SNR shock, and diagnosing the physical processes occurring in such an environment, thus a shape function is not required.

Figure 1. This schematic shows the exploding plasma geometry. Experiments are performed with and without a magnetic imposed on the whole experiment.

Figure 2. Shadowgraphy image shows density structures in the central collision region. These are observed only when a 7 T magnetic field is present.

Figure 3. An electron density profile inferred from colliding plasmas with a magnetic field and compared to data (dotted line) with no magnetic field.

An image of the plasma interaction at the scaled time of 500 ps is shown in Figure 2. The centre of the two dark regions in this image show the initial positions of the thin foils. The lasers strike the outside surfaces of each foil across a 1 mm diameter focal spot exploding the foils. An external 7 T magnetic field, produced using a pulsed electromagnet, is imposed on the experiment. Experiments using one exploding plasma show that the magnetic field does not affect the plasma expansion for over 1 ns following the foil explosion. Whilst comparison of colliding plasma experiments without and with the 7 T magnetic field shows that the collision in both cases begins at approximately 0.35 ns after the laser pulse, and that the subsequent collision is sensitive to the magnetic field. Magnetic field penetration may occur into the exploding plasma occurs due to an anomalous resistivity [3]. At the magnetic fields used here, the skin layer current density approaches the Alfvén limit, driving ion-acoustic or lower-hybrid instabilities. This suggests that the anomalous resistivity is sufficient to allow the magnetic field to penetrate into the plasma, and without a plasma-vacuum magnetic field interface.

New density features, the structures seen in the centre of the image in Figure 2, appear when a 7 T magnetic field is present. Interferometry measurements show that the density gradients are qualitatively different, with steeper density gradient close to the foil initial position and a low density plateau in the central region between the foils. The inferred electron density in the plateau region, compared to measurements with no magnetic field, is reproduced in Figure 3. These density features were not observed to evolve; this is probably due to increasing plasma density in the collision region at later time and weak magnetisation of the ions. For the experiment, we determine the ratio of the ion Larmor radius to \( L_{H} \) as 0.1 (i.e. 0.1 mm); this is large when compared to the ratio typical of a SNR (see Table 2), and the experimental value should be reduced by a factor of 10.

One solution is to reduce the ion Larmor radius, which scales as \( 1/B \), by increasing the magnetic field \( B \), this is possible but at the expense of reducing the plasma \( \beta \), which scales as \( 1/B^2 \), to near unity. A possible solution is to retain the colliding plasma scheme and maintain the large mfp’s and flow pressure whilst increasing both the magnetic field strength and the size of an experiment. This will require a sustained supersonic piston to drive the experiment; this may be possible using plasma jets.

Protostellar jets are characterised by highly supersonic flows (Mach numbers > 10) into surroundings that are underdense compared to the jet. These jets cool strongly by radiation. As a result of the cooling, the jets are believed to form thin dense shells that readily fragment into clumps. Since some protostellar jets are relatively close to Earth and they evolve on relatively short timescales, observational measurements are comprehensive and detail both jet structure and evolution. To compare jets from different objects, astrophysicists using three scaling parameters. These parameters
are the Mach number of the supersonic flow, the density ratio between the jet and surroundings, and a radiatively cooling parameter \[5\]. All jets are associated with accretion disks, and current understanding suggests that the launching and collimating mechanisms are related. Laser-plasma experiments can address the important topic of jet collimation, jet propagation and the effect jets have on the surrounding environment. \(Z\)-pinch experiments are addressing jet launch mechanisms \[2\].

One approach uses exploding plasmas to generate supersonic flows and colliding two or more plasmas to form a jet from the on axis stagnating plasma. The experimental geometry allows excellent diagnostic access, the introduction of an ambient gas or plasma and external magnetic fields. The stagnating plasma should form a jet with high \(Re\) and \(Pe\) minimising viscosity and thermal conduction, be highly collisional and radiate strongly. Laser-produced plasmas formed with mid to high atomic number materials such as aluminium and copper match these criteria. The simplest target uses two thin foils, placed at an angle to the central axis with the laser is incident from the outside of the ‘v’. The plasma of interest expands from the rear side of the foils, in a direction normal to the target surface. As the plasmas meet, there is a stagnation of the flows. Conservation of the axial momentum results in a bulk flow along the central axis, moving away from the collision region.

Table 3. Inferred dimensionless parameters of a protostellar jet compared measurement.

|                      | Proto jet \[4\] | Experiment \[5\] |
|----------------------|----------------|-----------------|
| Reynolds number, \(Re\) | \(10^7\)–\(10^7\) | \(10^6\)–\(10^7\) |
| Pécelt number, \(Pe\) | \(10^6\) | \(>100\) |
| Collisionality, \(ζ\) | \(10^6\)–\(10^6\) | \(10^6\)–\(10^6\) |
| Density contrast, \(η\) | \(1–20\) | \(10–50\) |
| Mach number, \(M\) | \(20–40\) | \(5–10\) |
| Radiative cooling, \(χ\) | \(0.1–10\) | \(0.1–1\) |

Interferometry and SOP data \[5\] show that experiments are promising. The results taken between 0 and 20 ns after the laser pulse show that a plasma jet forms and moves at \(\sim 300\) km/s and disassembles at late time. The presence of a background gas improves the jet collimation.

Analysis shows that the \(Re\) is high, and that the \(Pe\) is low indicating that thermal condition is important. The other parameters, as summarised in Table 3, scale well. A cooling parameter \(χ < 1\) shows that radiation lose is not dynamically important. In future work, \(Pe\) and \(χ\) must increase to eliminate thermal conduction and enhance radiative cooling respectively. This is possible by increasing the plasma density and reducing the temperature, and with the use of higher atomic number materials decrease the radiative cooling time.

Described are two experimental programmes to simulate astrophysical phenomena in the laser-plasma laboratory. The approach is to apply ideal plasma models to SNR shocks and protostellar jets and test the experimental plasmas against these models. In many cases, a rigorous scaling is not possible, and the scaling is adapted to ensure that experiments converge on dimensionless parameters relevant to astrophysics. Significant advances, including the use of external magnetic fields to induce collisionless behaviour are described. There is scope to improve techniques to reduce Larmor radius, reduce thermal conduction, and enhance radiative cooling in experiments. Future experiments will use magnetic fields to study the effects these fields have on plasma jet collimation, and then use jets as pistons to drive shocks over expended durations. Finally, the field of laboratory astrophysics is evolving rapidly. Laboratory astrophysics provides a common frontier for both the experimentalist and the theoretician interested in laboratory and astrophysical plasma research.

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