Stellar shocks and jets in the laboratory

Astronomy is primarily an observational science and most activity is associated with recording radiation emitted from atoms, molecules, and dense matter. An astrophysicist uses these measurements to develop a deeper understanding of the universe, basing this interpretation on our knowledge of physics and chemistry. The pursuit to understand our universe, rests firmly on our understanding of physics, and experiment (which may be particle, nuclear, or plasma experiments) is central to establishing this knowledge. As the conditions that prevail in space are often very different to those on earth, it is necessary to test our physics knowledge by creating or mimicking some extraordinary conditions in the laboratory.

Since the invention of the laser in 1960 by Ted Maiman, it was quickly realised that by focussing a high power pulsed laser, a small volume of plasma can be formed, exerting enormous pressures [1] in low density plasma and offering the potential for studying explosive phenomena such as shocks and jets. Research centres around the world have developed ever more powerful lasers, with the largest and most complex lasers developed for nuclear fusion research [2]. Modern lasers, such as Central Laser Facility's Vulcan, deliver a great deal of energy, in short pulses. On focusing these into a small area on a specially prepared target, pressures that can initially exceed a billion atmospheres or gigabars can be generated. These conditions occur nowhere else on earth and are comparable to the pressures present close to the centre of some stars. This has stimulated research campaigns to study the plasma physics of spectacular and dramatic events such supernova shocks, jets and possibly cosmic ray accelerators [3], see Figure 1.

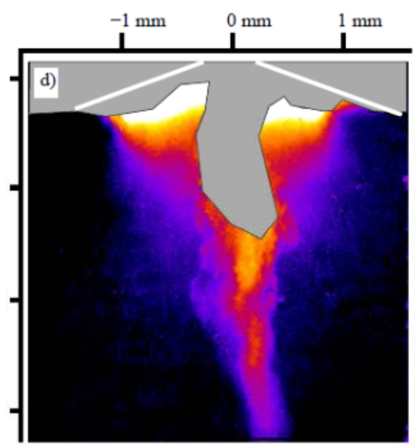

Figure 1. This image shows the electron density of a plasma jet as it moves downwards 10 ns after formation. The jet forms from the collision of plasmas created following laser-driven explosion of thin aluminium foils. The experiment scales to jets produced by Young Stellar Objects [4].

It is impossible to contain these pressures so these tiny laser-produced plasmas explode, and in a well designed experiment the exploding plasmas mimic shock waves or jets produced during the various phases of stellar evolution. There are practical limitations. Delivering these high powers, which are in the range of terawatts (10^{12} W) to petawatts (10^{15} W) or roughly 10 to 10,000 times the UK national electricity capacity, is possible but for only for brief periods. At the terawatt level these laser pulses last about a nanosecond, or 10^{-9} s (and a thousand times shorter for a petawatt), and focussed to regions 10 µm across. The plasma expands at about 1000 km/s to drive shocks that quickly expand to millimetres in size.

In comparison, the time and length scales associated with stars are very long. For example, as a large star dies it explodes quickly forming a supernova launching a shock into the interstellar plasma. This shock evolves for many thousands of years. The shock or supernova remnant initially expands at 10,000 km/s to occupy regions of interstellar space hundreds of light years in extent (one light year is about 10^{16} m). These shocks are collision*less*. This results in a rich and interesting of array of physics that does not ordinarily occur on earth. Of real interest to us are particle (or cosmic ray) acceleration, the generation and amplification of magnetic fields, and instabilities. Cosmic rays affect us all through stimulating cloud formation and driving genetic mutation processes.

On Earth, particle densities are typically 10^{19} in each cubic centimetre (10^{25} m^{-3}) and the particle mean-free-paths are less than a micron. This leads to collision*al* physics and the familiar atmospheric fluid flows. In the interstellar plasma, 1 particle in each cubic centimetre or 10^{6} m^{-3} is typical and huge mean-free-paths are normal so particles rarely collide. In this environment, collision*less* plasma waves dominate. Central to these plasma waves is the interaction of charged particles with a magnetic field and this interaction is very interesting not least as we need to ask how did this magnetic field arise in the first place, how does a shock form without collisions, and how do cosmic rays accelerate?

Reproducing aspects of astronomical plasmas, such as shock and jets, in the laboratory is demanding. It is possible due to scale invariance of much of the physics that govern the plasmas involved. We often use magneto-hydrodynamics (MHD) to scale across many orders-of-magnitude in time, space and density (and magnetic field) to establish a connection between the cosmos and the laboratory [5]. Recent developments include more generalised scaling approaches [6]. MHD describes many dynamical processes in astronomical plasmas including aspects of stellar evolution, shocks, the interstellar and planetary medium, nebulae and jets. However MHD is a simplified theory that applies to astronomical systems as they are so large. The physics not included in magneto-hydrodynamics is especially interesting as this describes wave-particle and other processes resulting in a collision*less* plasma allowing the growth of magnetic fields and the production of cosmic rays. Astronomical observations alone, cannot provide all the information necessary to understand how this variety of physics couples across very large scales in length, time, and density.

The challenge is twofold: first, create in a laser-plasma laboratory a scaled plasma and second, include the non-ideal or collision*less* physics in a way that allows shock formation, the growth of magnetic fields and particle acceleration. Steps towards this are illustrated in Figures 2 and 3. Here, two plasmas are created and driven towards each other using the Vulcan multi-beam terawatt laser. Images are taken as the plasmas interact giving measurements of spatial scales, flow speeds and density, and atomic spectroscopy gives measurements of the temperature and magnetic field [7]. These measurements combine, with computational modelling, to give details of the parameters necessary for scaling between the laboratory and a supernova remnant [8] essential for establishing the relevance of experiment to astrophysics.

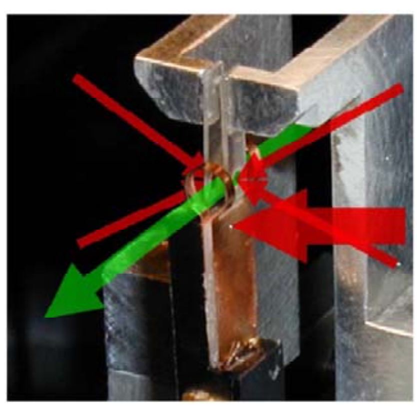

Figure 2. This photograph shows how the Vulcan laser was used to create a scaled astronomical plasma, in this case to scaled to a supernova remnant 100 years old. An intense laser, indicated by the large red arrow, creates a magnetic field, and

whilst four terawatt laser beams (red arrows) create the collision*less* plasmas. A sixth laser (green arrow) probes the interaction to provide a measurement.

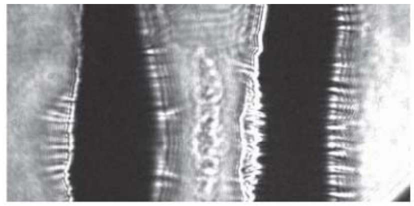

Figure 3. This probe image shows evidence for a collision*less* interaction between colliding plasma. The interactions occurs with an externally applied magnetic field at approximately 0.5 ns after laser formation of the plasmas, and scales to shock conditions typical of early age supernova remnants.

The design of an experiment fixes the initial conditions (for example the laser energy and intensity and target geometry), it is possible to repeat these experiments and change the initial conditions in controlled and known ways. A simple example, see Figure 4, is to study how quickly a shock or jet forms and expands from a point explosion, and repeating the experiment whether it is with different laser energy or materials.

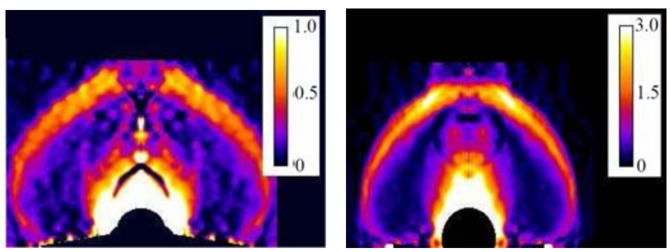

Figure 4. Electron density (in units of 10^{19} cm^{-3}) maps of shocks created by point explosions using the Astra laser. The shocks are collision*al* and form as the target material ablates into atmospheres of 10 mbar (left) and 50 mbar (right) of nitrogen.

With a petawatt laser and development of multi-petawatt lasers prospects for studying the physics associated with relativistic shocks, for example shocks in a gamma ray bursters, are being established [9]. Some ideas are well suited to Vulcan which can deliver both terawatt and petawatt laser pulses simultaneously. For example, it might be possible to recreate the acceleration of charged particles due to large-amplitude light waves. These light waves are thought to occur upstream of relativistic shock waves. The ability to create, and then interpret such extreme environments, in the laboratory is extraordinary, and might help solve some of the imponderables of astrophysics such as the source of ultra-high energy cosmic rays.

References

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