Laboratory Experiments of Stellar Jets From the Perspective of an Observer

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Abstract. It has been two decades since astronomers first discovered that accretion disks around young stars drive highly collimated supersonic jets. Thanks to concerted efforts to understand emission line ratios from jets, we know that velocity variations dominate the heating within these flows, and motions in stellar jets, now observed in real time, are primarily radial. The fluid dynamics of the cooling zones can be complex, with interacting shocks, clumps, and instabilities that could benefit from insights into the physics that only experiments can provide. Recent laboratory experiments have reproduced jets with velocities and Mach numbers similar to those within stellar jets, and the field seems poised to make significant advances by connecting observations and theories with experiments. This article points out several aspects of stellar jets that might be clarified by such experiments.

1. Introduction

A main focus of the HEDLA conferences has been to identify areas of possible overlap between astronomical observations and theory with laboratory experiments. Stellar jets are one promising possibility, because the physics that governs stellar jets is that of supersonic MHD flows, which is in principle amenable to experiment. We know a great deal about stellar jets because they radiate emission lines which reveal the densities, temperatures, velocities, and locations of shocks in the flow, and recent images of jets from HST show observable motions on the sky within a few years.

Space limitations prevent any overview of the field for this article. We refer the reader to Reipurth and Bally (2001) for a general review of stellar jets, and Hartigan (2003) for a summary of jet motions, magnetic properties, and techniques used to estimate mass loss. Eislöffel et al. (2000) and Hartigan et al. (2000) cover observations and interpretations of shocks in outflows, while Draine and McKee (1993) give a broad overview of shock waves in the interstellar medium, including processes related to supernova remnants, blast waves, and C-shocks.

Laboratory simulations have contributed little to our understanding of stellar jets to this point, though that situation is likely to change soon. Lebedev et al. (2002) have succeeded in creating a jet by vaporizing an array of wires and driving the plasma through a collimation shock similar to that envisioned by Canto and Rodriguez (1980). By running this jet into a crosswind, Ciardi et al. (2004) were able to reproduce a bent jet, like those observed when stellar jets emerge from a dense disk and encounter a large scale flow from another source (Lim and Raga, 1998). Being able to study the strength and stability of the deflection shock in the jet provides a unique insight into the physics of this process that is difficult to constrain observationally because the deflection shock may not heat the gas enough to become visible.

In what follows I point out areas like the one above where laboratory experiments could help observers and theoreticians make sense of the complexities within stellar jets. These examples focus on the fluid dynamics rather than on emission line ratios or line profiles, the latter probably impossible to simulate in the lab.

2. Variable Velocity Flows

Fluctuations in the jet velocity that exceed the local sound speed produce shocks when faster material overtakes slower material in the flow, and *this mechanism dominates the heating within stellar jets.* Evidence for variable velocity flows existed for decades in the emission line ratios, which indicate low shock velocities of ~ 30 km s^{-1} despite the fact that the jet moves at ~ 300 km s^{-1}. With new HST images of flows in the plane of the sky, one can measure the proper motions of individual knots with high precision, and differential motions within the jet are indeed ~ 30 km s^{-1}, as expected (Hartigan et al., 2001).

A natural consequence of a flow that varies in velocity is that individual bow shocks in the jet will occasionally collide. Figure 1 shows the aftermath of just such an event in HH 111, where two bow shocks lie in close proximity. The outer bow shock has a higher proper motion than the inner one; the motions imply that the shocks coincided about 80 years ago.

Colliding shocks like HH 111 L suggest a range of laboratory experiments relevant to astrophysical flows. An obvious experiment is to observe how working surfaces of the bow shocks evolve with time during the collision of the shocks, and to see if the collision generates any fragmentation. Because we know the velocity in jets like HH 111 at each point in the flow, if an experimenter could set up this velocity law in a laboratory jet then it would be possible to watch the jet evolve, with shocks and rarefaction waves developing and dissipating as they will hundreds of years in the future in the actual jet. The ability to create specified velocity law with time would open up other interesting possibilities. For example, jets that vary rapidly with time should form shocks close to the source, and then bunch up into distinct bullets at

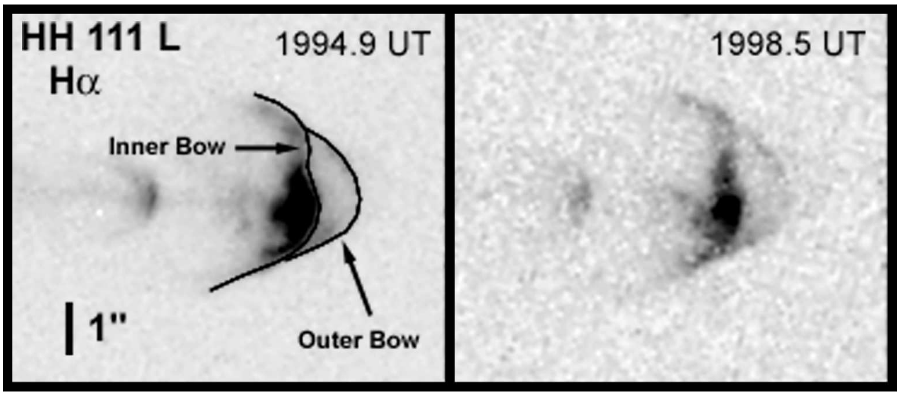

Figure 1. These images resolve the knot HH 111 L into two bow shocks. The faster bow shock, on the right, widened and faded between the two epochs. The two shocks coincided about 80 years ago. The scale bar is one arcsecond, or 6.9×10^{15} cm for all of the figures.

larger distances. Each shock tends to splatter material laterally, so the observed opening angle of the jet increases because of this process. Experiments should be able to quantify these ideas for real flows.

3. Interface Instabilities

Fig. 2 shows that the HH 34 bow shock breaks up into four evenly-spaced clumps which lag behind the main shock (Reipurth et al. 2002), a morphology which resembles that of a R-T instability (observed in real time!). A more prosaic explanation is that the preshock medium is clumpy, and the bow shock has overtaken clumps. Dynamical instabilities in shocks should be possible to study in the lab. Some issues to address include learning the conditions under which jets fragment, and when they do, if there is a characteristic fragmentation length. Identifying the physical process responsible for a preferred fragmentation scale is a key to understanding the flow dynamics.

4. Clumpy Flows

When a collimated jet strikes material ahead of it (in jets from young stars, typically previously ejected gas), a bow shock accelerates the ambient gas and a shock called the Mach disk decelerates the jet. Numerical simulations show that the 'working surface' region between these two shocks can be quite complex, and may host a variety of fluid and cooling instabilities (Frank et al., 2000; Blondin et al., 1990).

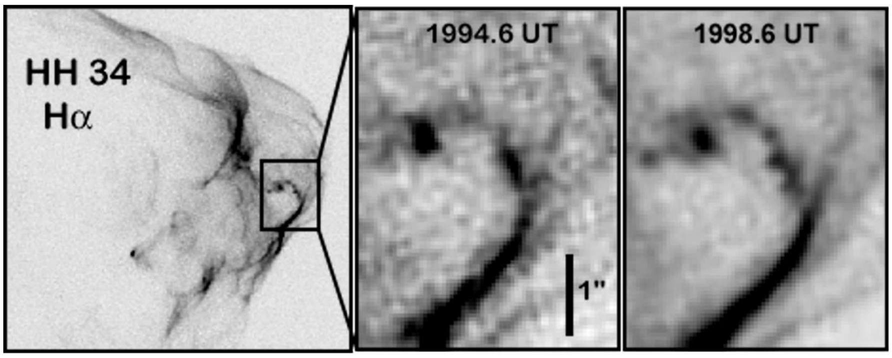

Figure 2. The boxed filament in the large bow shock of HH 34 marked in the figure either fragments, or encounters four distinct clumps between the two epochs.

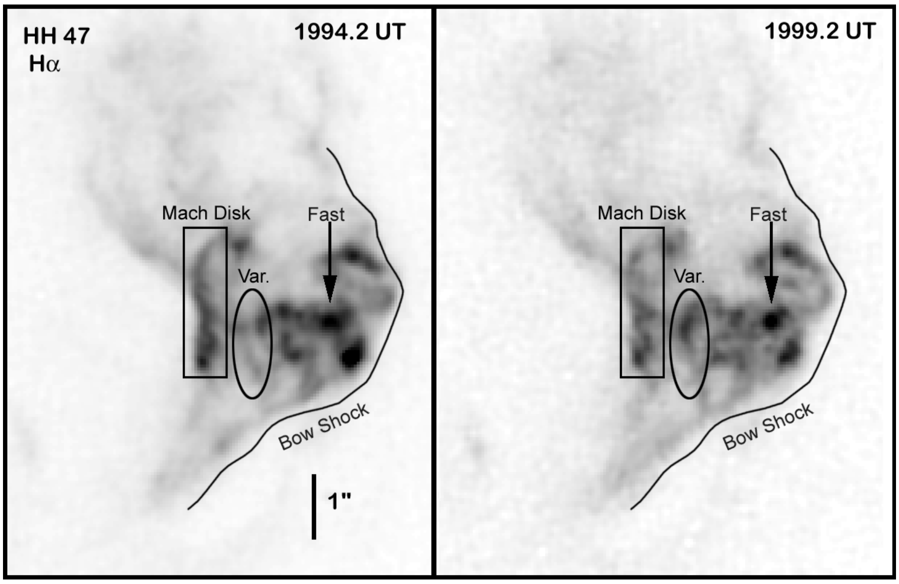

Figure 3. The working surface of HH 47A is the textbook example of a Mach Disk / bow shock pair. The system of shocks, which moves to the right in the figure, appears to be developing instabilities or has small clumps which plow through the Mach disk. The bright condensation labeled as 'fast' moves ahead of the other emission in the flow. The area marked 'Var' denotes a region where shocks appear to be forming.

Images of HH 47 (Figure 3) reveal yet another complication – the jet itself appears to be clumpy both along the jet and laterally to the jet. Between 1994 and 1999, the Mach disk began to break up, as if several denser clumps were passing through it. A very dense knot is now moving through the working surface, and should be emerging from the bow shock within a decade or so.

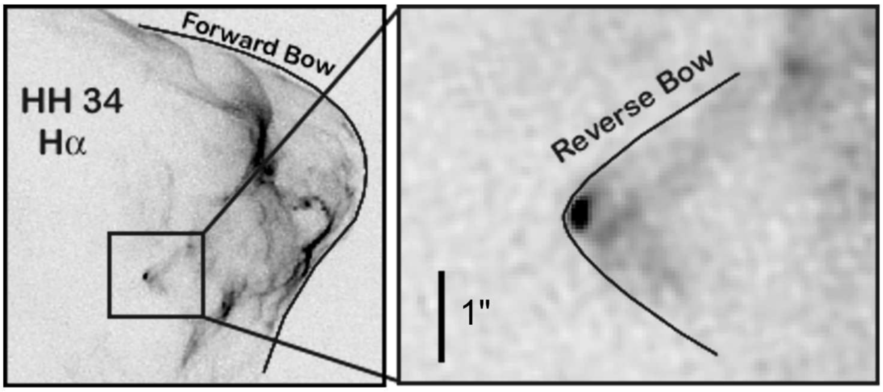

Figure 4. The knot indicated in the figure lies within the large bow shock of HH 34, but the small bow that forms around the knot is oriented as if it being entrained by faster material. The proper motion of this knot is slower than the rest of the flow, and material flows past it to the right.

There are several aspects of the dynamics within the working surface of HH 47 that could be clarified by experiments. Experiments could quantify the density contrast required to allow jet clumps to penetrate through the entire bow shock, and follow how the working surface changes with time. Determining how clumps affect the morphology of the Mach disk, and observing whether or not clumps fragment when they encounter shocks would be a substantial contribution to the subject.

5. Entrainment

Entrainment occurs within stellar jets as faster material overtakes slower material, and along the edges of bow shocks where shear exists (discussed in the next section). Along the jet we sometimes observe a slow clump being accelerated by a fast wind (Figure 4; Reipurth et al. 2002). These slow clumps then show 'reverse' bow shocks where the apex of the bow points in the direction of the exciting source (e.g. Schwartz 1978).

As clumps are accelerated by a supersonic wind, Kelvin-Helmholtz instabilities along the shock should begin to destroy the clump. Lab experiments could quantify this process, determining clump lifetimes for various density contrasts of the clump and the wind, clump sizes, wind velocities, magnetic field configurations, and so on.

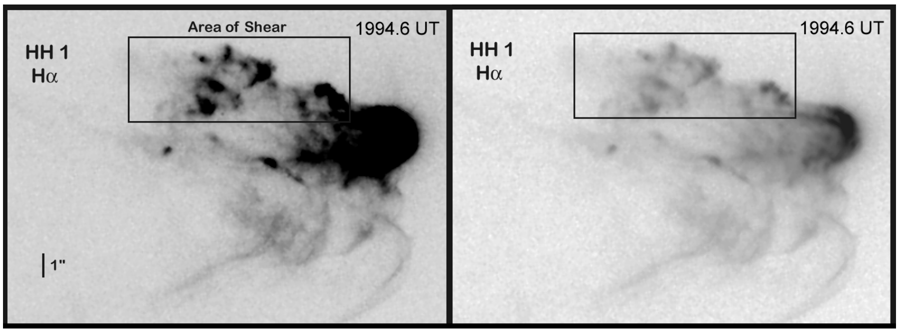

Figure 5. The boxed region of these Hα images of the HH 1 bow shock moves much more slowly, and appears clumpier than the arc-shaped shocks at the bottom of the images. This zone of shear is an excellent place to study fluid instabilities. The exciting source lies outside the images to the left. The two images are identical except for greyscale levels.

6. Supersonic Shear and Wakes

Images and movies of HH 1 show a remarkable zone of strong shear along the top portion of the large bow shock (Fig. 5; Bally et al. 2002). The morphology of the flow in that region lacks the smooth arcs of the bow shocks along the axis of the flow, and instead shows a clumpier morphology. The images suggest turbulent motions, or perhaps even vortices, in this region, which appears to be a real example of a supersonic mixing layer. Shear also appears to be tearing a piece of knot F from the HH 34 jet (Reipurth et al., 2002).

Although variations in the flow velocity dominate the heating within the majority of stellar jets, the HH 110 flow appears to result from a glancing collision of a jet and a dense molecular cloud. Images and proper motions of this object show the flow begins as a typical collimated jet, but suddenly fans out into a diffuse flow at an angle of about 45 degrees to the direction of the initial jet (Reipurth et al., 1996). The velocity structure within the wake is unusual for a jet, as it lacks any ordered structure (Riera et al., 2003).

Laboratory experiments can help us interpret images like HH 1 by determining the types of structures, such as shocks, clumps, and vortices, that occur in mixing layers with different amounts of supersonic shear, The HH 110 flow is an obvious target for the lab, where one could explore the velocity structure and morphologies of supersonic wakes of flows deflected by various angles with a range of velocities.

7. Concluding Remarks

Laboratory experiments have begun to make substantial contributions to our understanding of the dynamics of shocked astrophysical flows. Including variable velocities and clumps will be the biggest steps experimenters can make toward modeling the dynamics present in real astrophysical flows.

All the experiments outlined in this article would be greatly enhanced by including magnetic fields of various strengths and orientations within the flows. Modeling MHD flows is notoriously difficult when including non-LTE atomic cooling, and fields are also challenging to constrain observationally. Laboratory experiments may also be able to shed some light on how easily dust is heated and destroyed in shocks of various velocities, densities, and field strengths, and assess the extent to which dust is charged behind shocks. Another possibility would be to create a C-shock in the lab, which forms when the flow is supersonic but sub-Alvenic. In a C-shock, ions and neutrals act as separate fluids in the postshock gas, and friction between these fluids produces a spatially extended heating zone that is difficult to model theoretically and not easily resolved with current observations. C-shocks play a critical role in accelerating molecular outflows from young stars by transferring momentum and energy from stellar jets to the ambient molecular cloud.

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