Final Report.

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Colliding Magnetized Radiative Plasmas: Frontier Plasma Dynamics in the Lab and Astrophysics

Summary

This goal of this proposal was a focused study to understand multi-dimensional Colliding Magnetized Radiative Plasma flows (or CMRPs) relevant to basic plasma physics and jets in the context of stellar evolution astrophysics. The basis of this study is a suite of pulsed power experiments addressing: (1) the development and evolution of radiative instabilities in CMRP flows; (2) the role of magnetic fields in altering shock properties in complex multi-dimensional CMRP flows (Suzuki et al 2015). This project was planned as a theory/simulation compliment to DE- SC0020434 where the main project was new experiments. The principle goal in this work was focused on the rich dataset discussed in Suzuki-Vital 2015 which demanded a detailed theoretical interpretation. Our research program entailed carrying forward a campaign of high-resolution simulation studies using a state-of the-art AMR MHD multi-physics code developed in-house at the University of Rochester (AstroBEAR). From these simulations our team developed a stepwise understanding of the radiative MHD issues raised by the experiments. These included the formation of instabilities and the propagation of internal shocks waves. The simulation data allowed for to development of analytic theory accounting for behavior seen in the plasma experiments and extending to the kinds of astrophysical jets seen in both the early and late stages of star formation (Markwick et al 2021, 2022, 2024a,b).

In addition, our team also carried out a number of direct astrophysical hydro and MHD studies of jets and shock waves that expanded the understanding of topics such as the conditions under which jets form in binary stars as well as the nature of shock waves forming from the collision of stellar and planetary winds (Debrecht et al 2024, Zhou et al 2020,2022, Chamandy et al 2024, Guidarelli et al 2022).

Specific Projects

In this section we provide details about a subset of the projects carried out during the tenure of the grant.

Cooling and instabilities in colliding flows

Markwick et al 2021, 10.1093/mnras/stab2577

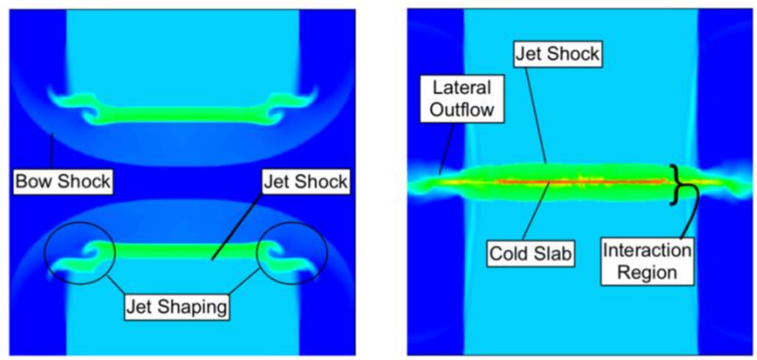

Figure 1. Identification of key components of the colliding jet systems before and after collision.

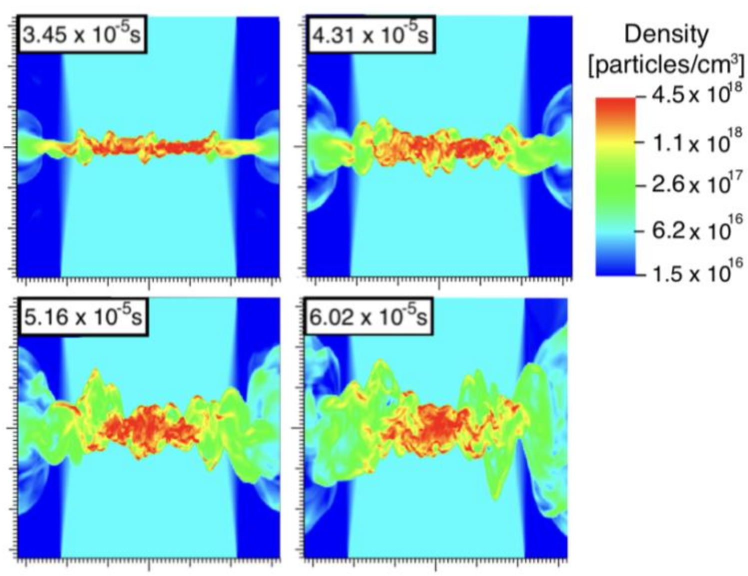

Figure 2. NTSI instabilities driving strong inhomogeneities in the interaction regions of colliding jets.

In this study we began our work investigating the basic plasma physics of collisional self-interactions such as those occurring in protostellar jets. These collisions give rise to strong shocks, the structure of which can be affected by radiative cooling within the flow. To study such colliding flows, we used the AstroBEAR AMR code to conduct hydrodynamic simulations in both one and three dimensions with a power law cooling function. The characteristic length and time scales for cooling are temperature dependent and thus vary as shocked gas cools. When the cooling length decreases sufficiently rapidly the system becomes unstable to the radiative shock instability, which produces oscillations in the position of the shock front. These oscillations can be seen in both the one and three dimensional cases.

We explored the role of these instabilities in creating the kinds of clumping seen in the experiments. In Suzuki Vital et al 2015 such clumps were associated thermal instabilities. However, our simulations showed no evidence of the inhomogeneities characteristic of a thermal instability, even when the cooling function met the expected criteria. In the three-dimensional case, the nonlinear thin shell instability (NTSI) was found to dominate when the cooling length is sufficiently small. When the flows are subjected to the radiative shock instability, oscillations in the size of the cooling region allow NTSI to occur at larger cooling lengths, though larger cooling lengths delay the onset of NTSI by increasing the oscillation period. In this way our work thus established a foundation for understanding which kinds of instabilities can occur in colliding flows in both laboratory and astrophysical settings.

Morphology of shocked lateral outflows in colliding hydrodynamic flows

Markwick et al 2022, 10.1063/5.0095166

In this study we again used the AstroBEAR AMR code to conduct hydrodynamic simulations of colliding plasma flows (jets) in three dimensions. Here we shifted our focus away from instabilities to a study of flow parameter variations, allowing us to better understand the conical shape and downward propagation of the bow shock and lateral outflows. The shape of the bow shocks withing the interaction region between the colliding jets was an important diagnostic in Suzuki-Vitral et al 2015

We introduced variations in the flow parameters of density, velocity, and cross-sectional radius of the colliding flows in order to study the propagation and conical shape of the bow shock formed by collisions between two, not necessarily symmetric, hypersonic flows. Our results showed that the motion of the interaction region is driven by imbalances in ram pressure between the two flows, while the conical structure of the bow shock is a result of shocked lateral outflows being deflected from the horizontal when the flows are of differing cross sections. We derived relations demonstrating that the simulation results could be recovered via analytic models which focused on specific features in flows. In particular we were able to demonstrate how the deflection angle of the shocked lateral flows depended on the Mach number and cooling strength within the flow.

$$\tan\theta = \left[\frac{(\gamma+1)(\gamma M^2+1)}{8\gamma\xi M^2+(\gamma+1)(\gamma+3)M}\right]\frac{r_+^2-r_-^2}{r_-^2}$$

Cooling and instabilities in colliding radiative flows with toroidal magnetic fields

Markwick 2024a, 10.1093/mnras/stae312

In the next study, we took the crucial step towards recovering the experiments by including magnetic fields in the simulations. When magnetic fields are present, additional structures can form within the interaction region. One-dimensional simulations of pulsed jets have found that colliding magnetized blobs can essentially 'bounce' off of one another as magnetic pressure increases in cooling zones behind the shocks. Other studies have investigated the lateral structure of this phenomenon with an axisymmetric model and found that while adiabatic shocks generate a net outward radial force in the jet column

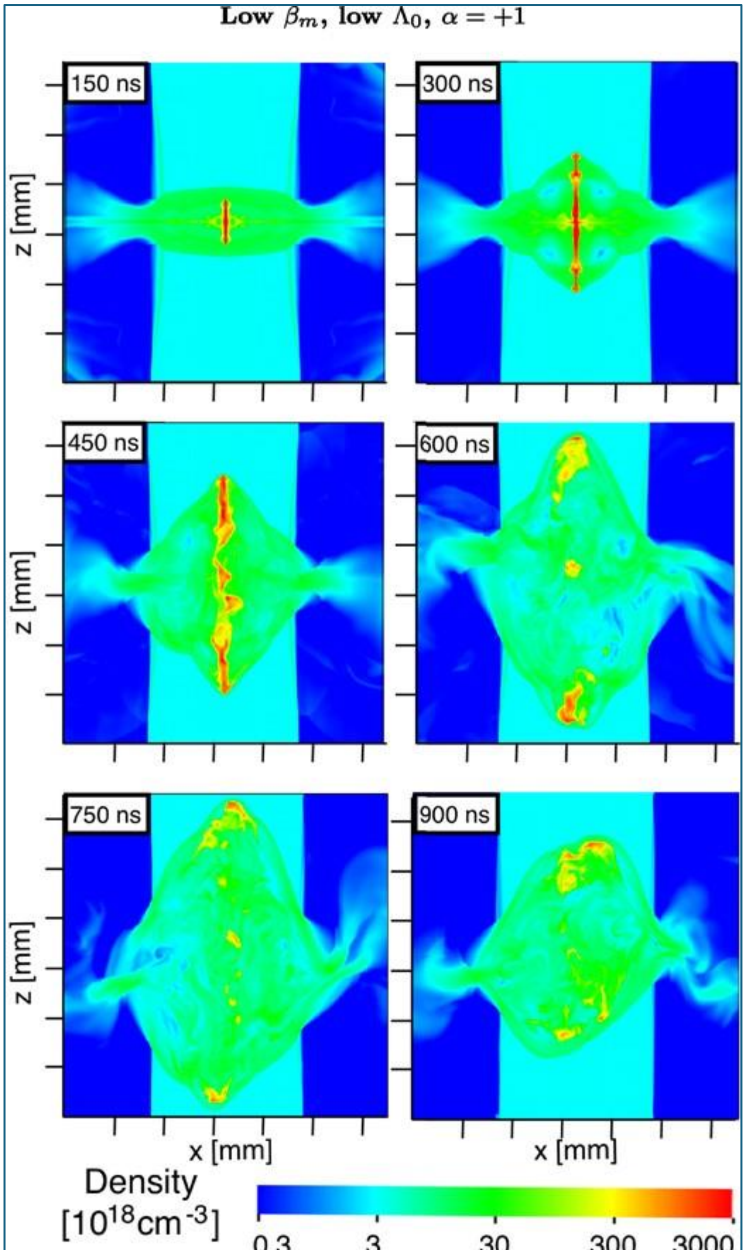

Figure 3. An MHD run which features a relatively strong magnetic field, along with weak cooling which weakens as temperature decreases. A prominent feature is the formation of a spine, driven by magnetic hoop stresses which eventually collapses due to instabilities.

from high post-shock pressures, the radial forces are inward for strongly cooled isothermal shocks because the increased post-shock magnetic pressure dominates the thermal pressure in that case. This inward motion produces a two-component structure: a disc and a spine. The disc spans the width of the interaction region in a manner similar to the cold slab in the hydrodynamic case (as discussed in Markwick et al. 2022), while the spine is the result of magnetic forces drawing cooled material towards the axis. The spine then expands along the *z*-axis and becomes a secondary jet that flows against the converging flows of the colliding columns (Figure 3).

Our results focused on the development of such “spines” and their interaction with the cold disk in order to understand how the instabilities explored in the first paper will be modified by magnetically driven structures. Our simulations showed that hoop stresses of the toroidal fields provides provide the collimating force that results in the emergence of a dense spine along the axis. We were further able to show that the growth speed of the spine is determined primarily by the strength of the magnetic fields. We derived an analytic relation for the increase in spine height h as a function of time that was well-matched by the simulation data.

$$\frac{\partial h_{\mathrm{s}}}{\partial t} = 2v_i \left(\frac{1}{\gamma M^2} + \frac{1}{M\sqrt{\gamma \beta_{\mathrm{m}}}} \right).$$

After some time, however, one or more instabilities of the kind investigated in the first paper, will contribute to the disruption of the interaction region. For flows with sufficient magnetic fields for spine formation, the spine eventually becomes unstable and collapses. For flows dominated by radiative cooling, the hydrodynamic instabilities studied in Markwick et al. (2021) will disrupt the cold slab, which in turn disrupts the spine at an earlier time than would occur as a result of the spine instability alone.

This study allowed us to make contact with the majority of dominant physics in the experiments (other than non-ideal plasma effects).

Other Jet Studies

Along with our direct work on the laboratory plasma experiments we also carried out studies of astrophysical plasma jets/winds/shocks and their origin. While grant supported a number of works, (Debrecht et al 2024, Zhou et al 2020, 2022, Chamandy et al 2024, Guidarelli et al 2022), here we report on just one of particular significance.

Jets from main sequence and white dwarf companions during common envelope evolution

Zou et al 2022 10.1093/mnras/stac1529

It has long been speculated that jet feedback from accretion on to the binary companion of a giant star during a common envelope (CE) event could affect the orbital evolution and envelope unbinding process. In Zou et al 2022 we presented global 3D hydrodynamical simulations of CE evolution (CEE) that included a jet subgrid model and compared them with an otherwise identical model without a jet. Our binary consisted of a 2-$M_{\odot}$ red giant branch primary and a 1- or 0.5-$M_{\odot}$ main sequence (MS) or white dwarf (WD) secondary companion modelled as a point particle.

We ran the simulations for 10 orbits (40 d) adding mass at a constant rate Mj of the order of the Eddington rate, with maximum velocity vj of the order of the escape speed, to two spherical sectors with the jet axis perpendicular to the orbital plane. We explored the influence of the jet on orbital evolution, envelope morphology and envelope unbinding, and assessed the dependence of the results on the jet mass-loss rate, launch speed, companion mass, opening angle, and accretion rate.

In line with our theoretical estimates, we found that the jets are choked around the time of first periastron passage and remain choked thereafter. Subsequent to choking, but not before, jets efficiently transfer energy to bound envelope material. This leads to increases in unbound mass of up to $\sim$ 10 per cent, as compared to the simulations without jets. We also estimate the cumulative effects of jets over a full CE phase, finding that jets launched by MS and WD companions are unlikely to dominate envelope unbinding.

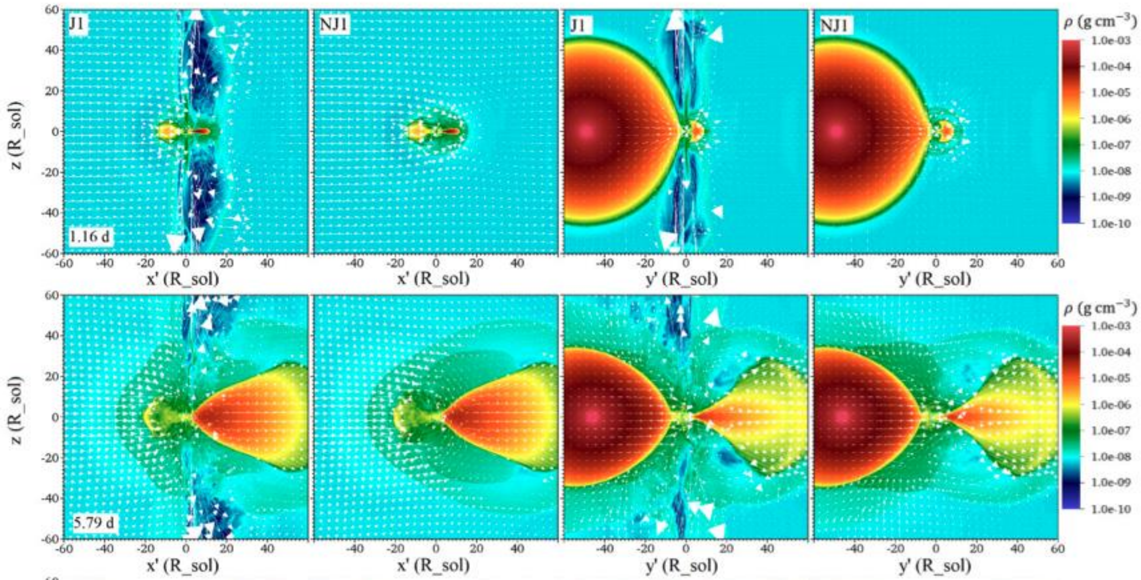

Figure 1 Time evolution of Common Envelope evolution in a binary system consisting of a Red Giant and a main sequence companion. Sequential density slices (top and bottom) through the line connecting the stars are shown for 2 different models (J1 and NJ1) at two different evolutionary stages. In J1 a jet is initially being driven via an accretion disk surrounding the main sequence star. As the system evolves the jet is choked off (see Zhou et al 2022) for further detail).

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