Study of shock waves and related phenomena motivated by astrophysics

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Abstract. This paper discusses the recent research in High-Energy-Density Physics at our Center. Our work in complex hydrodynamics is now focused on mode coupling in the Richtmyer-Meshkov process and on the supersonic Kelvin-Helmholtz instability. These processes are believed to occur in a wide range of astrophysical circumstances. In radiation hydrodynamics, we are studying radiative reverse shocks relevant to cataclysmic variable stars. Our work on magnetized flows seeks to produce magnetized jets and study their interactions. We build the targets for all these experiments, and simulate them using our CRASH code. We also conduct diagnostic research, focused primarily on imaging x-ray spectroscopy and its applications to scattering and fluorescence.

1. Introduction
In our Center for Laser Experimental Astrophysics Research, we explore fundamental processes in high-energy-density (HED) physics that are relevant to astrophysics, working with systems that feature shock waves or other high-Mach-number flows. This research at present is in several areas, which we discuss separately in the following. Many of our experiments are done at the Omega laser facility \cite{1}, while others are done elsewhere. The Omega experiments are our primary focus here. These experiments require complex targets, which we assemble at Michigan \cite{2}. We also need simulations to design and analyze the experiments. We do this primarily with our CRASH code \cite{3}.

2. Complex Hydrodynamics
Our studies of complex hydrodynamics examine the nonlinear development of the basic instabilities that develop in dynamic media and that may evolve into turbulence. Our present focus is on the use of Omega EP, which can drive mm-scale areas for up to 30 ns while reserving one beam for diagnostics. This has enabled us to design \cite{4} and field the first HED, Richtmyer-Meshkov experiment in which the shock wave proceeds from a denser to a less dense material,
allowing a clean examination of the phenomenon of mode coupling. We drive a steady shock through an interface having a perturbation with modes of 5% amplitude at 100 \( \mu m \) and 50 \( \mu m \) wavelengths. Figure 1 shows a radiographic image obtained using a spherical crystal imager operating at the K\( \alpha \) line of Cu. One can see that the structure has grown to large amplitude and become geometrically complex. Analysis of the interface structure shows that mode coupling has become important [5]. Using a similar experimental design, we are initiating experiments on the Kelvin-Helmholtz instability [6]. In related work we are the lead group for an experiment [7] to study radiative effects on the Rayleigh-Taylor instability [8] at the National Ignition Facility [9].

3. Radiation Hydrodynamics

HED facilities have made it possible to undertake fundamental experiments on radiation hydrodynamics, in which the flow of radiative energy alters the hydrodynamic structure of a system. Following extensive work with driven radiative shocks, in which a “piston” of Be plasma drives a shock wave down a tube of Xe or Ar gas [10] [11] [12] [13], our emphasis has turned to the study of radiative reverse shocks, in which a supersonic flow is impeded by an obstacle. This configuration is relevant to the class of cataclysmic variable stars in which an incoming flow strikes an accretion disk at an oblique angle.

Figure 2 shows the experimental structure and some radiographic data. The 4 mm expansion distance enables the radiative shock to be sustained for tens of ns. Our experiments have included shocks formed at normal incidence and at oblique incidence [14], as shown in the figure. A future challenge is to replace the Al obstacle used now, with a flowing plasma. This system is well scaled to the astrophysical case.

4. Magnetized Flows

Our work with magnetized flows is aimed toward the study of interacting systems that produce magnetic field amplification within a turbulent flow, such as the flow-driven accretion disk discussed by Ryutov [15]. As a first step, we have developed a long-duration plasma jet by the irradiation of the outer surface of a conical target. This produces a supersonic flow that converges on axis, producing a jet initially confined by shocks.
By embedding this target within the equatorial plane of a cusp magnetic field we can produce a magnetized flow with the potential to amplify the frozen-in field lines as two or more jets collide.

The experiments on Omega produce a jet having a velocity above 100 km/s; the plasma produced by jet collisions will have a magnetic Reynolds number of about 100. Figure 3 shows one such jet and the jet velocities of opposing jets, measured using Thomson scattering of UV light.

5. X-ray imaging
As is evident from the above data, a key diagnostic for much of our research is x-ray imaging, which has led to our involvement in improved x-ray diagnostics. Recently, our focus has been on imaging x-ray Thomson scattering (XRTS). In collaboration with Los Alamos National Laboratory, we developed an imaging x-ray spectrometer that could be fielded on Omega [16]. Using it, we obtained the first simultaneous measurements of profiles of temperature, density, and ionization in experiments in which a blast wave was driven into foam. This provided one of the few consistency tests to date of the properties inferred from XRTS [17]. Figures 4 and 5 show a schematic of this experiment and examples of the data.

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