Lecture 1

Introduction to Radiation-Hydrodynamics

The equations of radiation-hydrodynamics consist of the equations of thermal radiation transport coupled with the equations of fluid dynamics. Material emits radiation in the form of photons as a function of temperature, and photons deposit both energy and momentum in the material through scattering and absorption interactions. The density of internal energy in matter is proportional to T, but the density of thermal radiation energy is proportional to T^4. Thus at sufficiently high temperatures, all material takes the form of a fluid plasma with the thermal radiation energy density completely dominating the material internal energy density. If one is to model the dynamics of such materials, the effect of thermal radiation must clearly be taken in to account. Radiation-hydrodynamics plays a major role in high energy density physics: supernova explosions, inertial confinement fusion, Z-pinch radiation sources, etc.

The radiation transport in radiation-hydrodynamics is complicated by the motion of the fluid because standard interaction cross sections are defined for a material at rest. There are two choices for dealing with material motion. The first is to continue to express the transport equation in the standard laboratory frame and make appropriate changes to the cross sections to account for the motion. The second is to transform the transport equation to a frame in which the particle velocity is measured relative to the local material velocity, i.e., a particle with zero velocity is moving with the material. This is known as the comoving frame formulation. While this formulation enables the use of standard cross sections, the comoving frame is a non-inertial reference frame. Conservation statements can only be made by transforming to the laboratory frame. This makes it difficult to define conservative numerical methods for the comoving-frame transport equation. Fortunately, we will consider only non-relativistic flows, which enables significant simplifications to be made in the treatment of material motion. An unfortunate aspect of non-relativistic flows is that we cannot obtain equations that are frame-invariant without using a fully-relativistic treatment. The non-relativistic hydrodynamics equations are Galilean invariant, but there is no such thing as the non-relativistic radiation transport equation because photons travel at the speed of light and thus are always relativistic. A very useful approximation that yields reasonably simple equations that are easily understood is the grey radiation diffusion approximation. Using neutron transport terminology, this would be called a one-group diffusion approximation.

There are two basic numerical approaches to hydrodynamics calculations. The first is called the Eulerian approach and is characterized by a fixed mesh through which the fluid moves. This method can treat essentially any type of flow, but material interfaces are problematic because they generally only coincide with mesh interfaces at the beginning of a calculation. The second is called the Lagrangian approach and is characterized by a mesh that moves with the fluid. Material interfaces can be accurately treated since a material interface that initially coincides with mesh interface retains this coincidence throughout the calculation. Lagrangian methods are generally limited to problems in which fluid does not enter or exit the problem domain. Furthermore, Lagrangian methods generally fail in multidimensional problems with rotational flows because the mesh becomes entangled. Lagrangian methods are ideal for 1-D problems since rotational flows are not possible.

Students in this class will develop a 1-D radiation-hydrodynamics code based upon grey radiation diffusion and either Lagrangian or Eulerian hydrodynamics. This code will be used to computationally study radiatively-driven shock waves. For more information on course content, see the syllabus.