1
Introduction

1.1 Philosophy

The discipline of radiation hydrodynamics is the branch of hydrodynamics in which the moving fluid absorbs and emits electromagnetic radiation, and in so doing modifies its dynamical behavior. That is, the net gain or loss of energy by parcels of the fluid material through absorption or emission of radiation is sufficient to change the pressure of the material, and therefore change its motion; alternatively, the net momentum exchange between radiation and matter may alter the motion of the matter directly. Ignoring the radiation contributions to energy and momentum will give a wrong prediction of the hydrodynamic motion when the correct description is radiation hydrodynamics.

Of course, there are circumstances when a large quantity of radiation is present, yet can be ignored without causing the model to be in error. This happens when radiation from an exterior source streams through the problem, but the latter is so transparent that the energy and momentum coupling is negligible. Everything we say about radiation hydrodynamics applies equally well to neutrinos and photons (apart from the Einstein relations, specific to bosons), but in almost every area of astrophysics neutrino hydrodynamics is ignored, simply because the systems are exceedingly transparent to neutrinos, even though the energy flux in neutrinos may be substantial.

Another place where we can do "radiation hydrodynamics" without using any sophisticated theory is deep within stars or other bodies, where the material is so opaque to the radiation that the mean free path of photons is entirely negligible compared with the size of the system, the distance over which any fluid quantity varies, and so on. In this case we can suppose that the radiation is in equilibrium with the matter locally, and its energy, pressure, and momentum can be lumped in with those of the rest of the fluid. That is, it is no more necessary to distinguish photons from atoms, nuclei, and electrons than it is to distinguish hydrogen atoms from helium atoms, for instance. They are all just components of a mixed fluid in this case.

So why do we have a special subject called "radiation hydrodynamics", when photons are just one of the many kinds of particles that comprise our fluid? The reason is that photons couple rather weakly to the atoms, ions, and electrons, much more weakly than those particles couple with each other. Nor is the matter–radiation coupling negligible in many problems, since the star or nebula may be millions of mean free paths in extent. Radiation hydrodynamics exists as a discipline to treat those problems for which the energy and momentum coupling terms between matter and radiation are important, and for which, since the photon mean free path is neither extremely large nor extremely small compared with the size of the system, the radiation field is not very easy to calculate.

In the theoretical development of this subject, many of the relations are presented in a form that is described as approximate, and perhaps accurate only to order of v/c. This makes the discussion cumbersome. Why are we required to do this? It is because we are using Newtonian mechanics to treat our fluid, yet its photon component is intrinsically relativistic; the particles travel at the speed of light. There is a perfectly consistent relativistic kinetic theory, and a corresponding relativistic theory of fluid mechanics, which is perfectly suited to describing the photon gas. But it is cumbersome to use this for the fluid in general, and we prefer to avoid it for cases in which the flow velocity satisfies $v \ll c$. The price we pay is to spend extra effort making sure that the source-sink terms relating to our relativistic gas component are included in the equations of motion in a form that preserves overall conservation of energy and momentum, something that would be automatic if the relativistic equations were used throughout.

Some general references on the subject of radiation hydrodynamics are these:

- The most comprehensive general reference is *Foundations of Radiation Hydrodynamics*, by Mihalas and Mihalas (1984). This provides all the needed background in statistical physics, hydrodynamics, and radiative transfer, as well as a thorough discussion of the nonrelativistic and relativistic formulations of radiation hydrodynamics, mostly in one space dimension. The applications include several of the more important topics as of 1984.
- The book *The Equations of Radiation Hydrodynamics* by Pomraning (1973) reflects the viewpoint of the neutron transport community, in that the $O(v/c)$ effects are discussed largely in the fixed frame, and the distinction between fixed-frame diffusion and comoving-frame diffusion is not made sufficiently clear. Considerable space is devoted to Compton scattering with frequency redistribution, a small effect in astrophysics (except for hard x-rays) although the analogous problem in neutron transport is important.
- The NATO workshop *Astrophysical Radiation Hydrodynamics*, edited by Winkler and Norman (1982), contains useful articles on the fundamental theory by Mihalas,

on advanced computational methods in hydrodynamics by Norman and Winkler and by Woodward, on particle methods by Eastwood and on finite-element methods by Griffiths.

- *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena* by Zel'dovich and Raizer (1967) is one of the most valuable references for radiation hydrodynamics in general. The treatment of radiation here is simplified, but the insightful analysis of complicated shock phenomena is outstanding.
- *Stellar Atmosphere Modeling*, edited by Hubeny, Mihalas, and Werner (2003), is the most recent (in 2003) conference devoted to the advanced methods in numerical radiation transport for astrophysics.
- *A Guide to the Literature on Quantitative Spectroscopy in Astrophysics* by Mihalas (2003) is a comprehensive bibliography on astrophysical radiative transfer and related topics, and includes a 30-page historical review of the field.

1.2 Outline

The succeeding chapters of the book start with an introduction to gas dynamics that covers the essential elements: Euler's equations, the Lagrangian equations, and the especially important topic for numerical calculations, arbitrary Lagrangian Eulerian (ALE). Then comes viscosity and the Navier–Stokes equation, Bernoulli's equation, and some of the important topics like sound waves, shocks, and the self-similar Taylor–Sedov blast wave. The following chapter is a fairly up-to-date survey of methods for numerical hydrodynamics, which is divided into Lagrangian, Eulerian, and ALE, with special notice for methods such as Godunov's and the weighted-essentially-nonoscillatory (WENO) methods.

Next we go on to three chapters on radiation and radiative transfer at increasing levels of complexity. The first chapter gives the basic definitions of things like the intensity, angle and frequency moments, the idea of diffusion, and the initial, more naive view of how radiation affects the state of the gas. The second radiation chapter deals with the simple methods for steady-state radiative transfer, and introduces some key ideas like Milne's equations and the Eddington–Barbier relation. The third radiation chapter in this group introduces the special-relativistic picture of radiation transport in all its complexity, and then attempts to wash away the dross and leave a simple enough picture of the dynamics of radiation and matter when the matter does not move *too* fast ($v \ll c$) that it can be incorporated into practical calculations.

Once we are fully apprised of the true way in which matter is coupled to radiation we return to some analytical examples of gas dynamics coupled now with radiation, including the modifications to wave motion due to energy and momentum coupling.

The following chapter deals with the atomic details of the processes that actually couple radiation and matter; these are the source-sink terms that appear in the conservation equations for matter and radiation separately. We can talk *about* the quantum mechanics that enters the calculations of these interactions, but the real work is done in computer codes such as OPAL that supply radiative process data to hydrodynamic simulations.

Next is a chapter on the most detailed methods for calculating the transport of spectral line radiation through a gas, when the radiative processes are dominant over the effects of electron–atom collisions to such a degree that the detailed quantum state of the matter is altered by this radiation which is not representative of the local thermal equilibrium distribution. This is the topic that is called non-LTE, where LTE stands for local thermodynamic equilibrium. The non-LTE condition is prevalent in many astrophysical and laboratory plasmas. The chapter describes the general features of non-LTE calculations, and then examines some interesting details of non-LTE line transport associated with frequency redistribution or the lack of it.

The next chapter concerns a subject often overlooked in treatments of radiative transfer, namely the effects of refraction and polarization on the radiation. Polarization is an important aspect of the measurements of radiation from the sun, and it may have increasing importance in observations of other bodies and in laboratory experiments as the quality of the data improves.

The next-to-last chapter is a survey of numerical methods of various kinds that are applied to radiation, either by itself or coupled with hydrodynamics. In a survey like this the names of the methods, some pointers into the literature, and summaries of what they are about is the limit of what can be presented in the space available, but it hoped that the reader will be enticed into reading more deeply.

The final chapter gives a short selection of radiation-dominated examples that either are important in themselves or bring out some interesting aspects of the theory.