PROBLEMS IN ASTROPHYSICAL FLUID DYNAMICS

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Summary The variety of fluid processes observed throughout the universe staggers the imagination, yet the subject has not attracted nearly as much serious interest from professional fluid dynamicists, as have geophysical fluid problems. Yet, in the sixties and seventies of the previous century, several symposia were held that brought astrophysicists and fluid dynamicists together under various titles such as Cosmical Gas Dynamics; we might even follow Lighthill's lead in another subject and speak of Astrofluiddynamics. Those old symposia were well attended and quite stimulating.

To give an idea of the kinds of problems that arise in astrophysics I outline here a (subjective!) selection of fluid dynamical problems faced by astrophysicists. I begin with thermal instability, a characteristic process discussed in astrophysics and this flows naturally into the larger domain of radiative fluid dynamics wherein radiation affects the dynamics both thermally and dynamically and also plays a significant role in the observations. Astrophysicists must also face the problems associated with long mean free paths in plasmas and in their gravitational analogues – gases whose constituent particles are stars or even galaxies. As time permits, I shall also speak of fluid dynamics in accretion disks and rotational processes in the sun.

This selection only scratches the surface of the subject and it is meant to be introductory. My subject is really astrophysically motivated fluid dynamics and the approach to be used in this discourse is largely analytic. However, I would stress that, on the hard core astrophysical side, progress is being made largely in the development of simulations. This is true throughout the subject, and is especially evident in a wide range of compressible flows such are encountered in stellar convection, the dynamics of interstellar gas clouds and in the formation of large-scale structure in the early universe.

THERMAL OVERSTABILITY

A uniform medium that is heated by some mechanical process and cooled radiatively can reach a stationary state given some simple conditions such as hydrostatic equilibrium. In typical situations, a slight increase in temperature leads to an increased cooling that restores the equilibrium temperature. However, in some cases, an increase in temperature may destroy the radiating atoms, and thus lead to a *decrease* in temperature, hence to instability. This situation may arise in the solar corona, in the interstellar medium and in other contexts. As the temperature is further increased, a new radiator takes over and a new equilibrium temperature is achieved. In this way, a mix of equilibria may be found and the result is thought to be the formation of clouds in a multi-temperature medium.

When the linear fluid dynamical theory of such situations also contains oscillatory modes, as it does in stratified media, the instability takes the form of growing, propagating waves. In the weakly nonlinear cases, nonlinear propagating waves are found that may be analyzed by the methods familiar in modern pattern dynamics.

PHOTOFLUIDYNAMICS

Radiative transfer is important in most cosmic bodies and the thermal aspects have been crucial in the study of the structure and internal dynamics of stars and related objects. Radiative fluid dynamics becomes more complicated in hot objects, of which there are many varieties, the simplest of which are stars whose masses are sixty or so times that of the sun and the currently most studied are hot accretion disks and the early universe. When the temperature is high, the pressure of the radiation can be at least as large as that of the material fluid and, in one vision of the situation, we have a two-fluid situation. An interesting situation in hot stars where radiation from below is forces its way through the outer layers to escape. The radiation exerts a levitating force on the medium and, when that force balances the gravitational force, we may expect the dynamics to have some similarities to that of fluidized beds. One may expect photon bubbles to form and this may play a role in explaining the great breadth of spectral lines in hot stars that indicate (what some believe) is supersonic turbulence. Hot stars rotate rapidly and one may wonder whether the this will lead to bubble merger and the formation of vortices. These allow rapid escape of radiation in beams that keep the vortices alive. There are many interesting issues in this subject, not the least of which is the development of adequate approximations that may permit the deepening of our understanding of these rich dynamical processes.

RAREFIED GAS DYNAMICS

As in the problems of radiative transfer, when the mean free paths of the constituent material particles of a fluid become comparable to or larger than the macroscopic scales of motion, the Navier-Stokes equations cease to be accurate. This difficulty must be faced in many problems of astrophysical fluid dynamics from the expected ones in astrophysical plasmas to the gravitational N-body problems in which the bodies may be stars or even galaxies. The issue of whether to improve matters by seeking of improved continuum approximations or directly by working with the kinetic equations is very interesting. Both approaches have their defenders. Perhaps an intermediate approach is appropriate as will be discussed.

VORTICES IN DISKS

Disks commonly form around central objects that are frequently compact. Such structures form in double stars, in galactic center and around newly formed stars with the main radial force balance being between the inward gravitational force and the centrifugal outward force. Many disks are quite thin and a shallow layer approximation may be appropriate for their study in many instances. The linear instabilities that may occur include gyromagnetic instability in which magnetic fields lead to the disorganization the shear flow in the disks and possibly conventional convective instability. The situation with respect to nonlinear instability is controversial. It is however generally agreed that disks are turbulent and this may be the means by which angular momentum in disks is carried outward so that the matter in the disks may be slowly being accreted onto the central object. If disks are like other rotating turbulent fluids, the should form vortices (or perhaps coherent magnetic flux tubes). These play an interesting role in the light variation in hot disks. In the case of cool disks that are thought to become planetary systems, vortices play a remarkable role in sucking in dust particles where they may coalesce to form large objects on the way to planet formation.

SOLAR DIFFERENTIAL ROTATION

As in geophysical fluid dynamics, the interplay of rotation and stratification is important in many cosmic situations. A nearby example is provided by the sun. The outer third of the sun is convective and has relatively low density. The inner two thirds is stably stratified and of higher density. The object as a whole rotates with a period of 28 days. The differential rotation in the convection zone is rather different from that of the interior as determined by helioseismology. The two regions are coupled through a convective boundary layer and a rotational transition layer called the tachocline. The situation is vaguely reminiscent of the terrestrial configuration where the outer layer is the atmosphere, the inner core the ocean and the tachocline is like the oceanographic thermocline. In both cases there seems to be a problem of these layers keep themselves so thin and do not suffer turbulent or diffusive spreading on the times available. Heretofore, as in the older approaches, attention has mainly focused on the influence of the convective layers on the interior, but the time is clearly ripe to look at the coupled system as is being done in studies of the ocean-atmosphere interactions.