Protostellar disks and the Primitive Solar Nebula

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(1) Turbulence in the solar nebula. This is a new project that we expect to figure prominently in our future work. The objective is to obtain quantitave information on the turbulent transport of mass, angular momentum and energy under the conditions that characterized the solar nebula, by direct numerical calculations. These calculations have been made possible by research conducted on new supercomputers (Cray XMP and Cray 2) by the Ames Computational Fluid Dynamics Branch, with whom we have established a strong collaboration. Techniques have been developed that permit the accurate representation of turbulent flows over the full range of important eddy sizes -- from the largest scales at which energy is deposited in turbulent motions, down through the inertial sub-range, to the small scales at which viscous dissiptaion becomes important. So far, these techniques have been applied (and verified) primarily in mundane laboratory situations, but they have a strong potential for astrophysical applications.

Most current models of the solar nebula are based on the hypothesis that turbulent stresses drive its evolution. But disagreement exists on the effectiveness, or intensity, of the turbulence. All models are burdened by untested assumptions regarding the details of the driving mechanisms, the vertical distribution of dissipated energy, and the all-important effects of rotation. Our approach is to conduct a sequence of numerical experiments to evaluate the Reynold's stress tensor, turbulent heat transfer rate, turbulent dissipation rate, and turbulent kinetic energy spectrum, as functions of position, for conditions relevant to the solar nebula. Emphasis is placed on the variation of these properties with appropriate nondimensional quantities (such as the Rayleigh, Taylor, and Prandtl numbers), so that relations can be derived that will be useful for disk modeling under a variety of hypotheses and initial conditions. In these experiments, we intend to examine separately the characteristics of three potential sources of turbulence in the nebula: thermal convection, mass infall from outside the nebula, and shear in the angular velocity.

The codes that were developed for engineering purposes require modification and generalization in a number of areas to realize their full potential for nebula studies, and this is where our efforts have been devoted so far. Calculations of Benard convection and convection driven by internal heat sources have been performed. Diagnostics have been devloped that permit easy examination of turbulent correlation coefficients, energy spectra, mean variable profiles, all evaluated at selected locations in the computational grid. The convection results have been compared with detailed experimental results and those of other numerical computations to the point where we are confident that our resolutions, computational grid size, integration time, etc. are adequated. We are now embarking on a series of experiments that will become progressively more general and complex, as we (1) obtain results for parameter ranges more relevant to nebula studies (e.g. low Prandtl numbers) that have not been previously examined, and (2) include more physical effects that will be necessary for our goal of understanding nebula turbulence.

(2) Self-gravitating Disk Models. Most models of the solar nebula ignore the self-gravity of the disk compared to that of the protosun. In many circumstances this is a good approximation, but it is clearly inadequate for gravitational instability of the disk, to form spiral density waves, planets or multiple star systems, say, should treat the gravitational field of the disk self-consistently. So far, this has only been attempted in studies that use hydrodynamical codes to calculate the collapse of protostellar clouds. However, the results of theses calculations are usually not the formation of a solar nebula-like disk, but rings or ring fragments (see review by Bodenheimer and Black, in Protostars and Planets, U. of Arizona Press, 1978), or in some cases, thick disks that are subject to non-axisymmetric instabilities (Boss, Icarus, 61, 3, 1985). In some cases, an ad hoc turbulence is added to transport angular momentum outward, allowing a disk to form (Morfill et al., in Protostars and Planets II, U. of Arizona Press, 1985). These results contrast with semi-analytic calculations of cloud collapse by Terebey et al. (Ap. J., 286,529,1984), which suggest that a slowly rotating cloud can collapse directly to a disk.

In order to examine the ring/disk formation question, as well as to provide a convenient method for studying self-gravitating disk models for other purposes, we have devised a method whereby (nearly) arbitrary distributions of mass and angular momentum in spherically symmetric protostellar clouds can be mapped into corresponding distributions in infinitely thin self-gravitating disks, under the assumption of strict angular momentum conservation. The method is based on Toomre's (Ap. J., 138, 385, 1963) Bessel integral formulation for the mass distribution in flattened galaxies. Solution of an integral equation, by an iterative method, is required; but what appears to be an excellent first approximation for the mass distribution in the disk can be found analytically for many cases. These preliminary results agree very closely with the corresponding results of Cassen and Moosman (Icarus, 48, 353, 1981) for inviscid disks. Furthermore, they suggest that disks (rather than rings) can form a wide range of initial cloud conditions, even at high rotation rates, as long as enough accretional energy can be radiated away so that the thin disk approximation is valid. Calculations of the cooling of the post-accretion shock gas indicate that this is the case. The implication is that numerical collapse calculations must resolve the accretion shock cooling region very well in order to get accurate results, even on the basic question of ring- vs. disk formation.

(3) Analysis and interpretation of meteoritic inclusions. Examination of the components of the Allende meteorite has continued, along with the development of a model postulated to explain the observed thermal processing of CAIs (see Bunch et al., Lunar Planet. Sci. XVI, 97, 1985; Cassen et al. ibid. 117, 1985; Bunch et al., Lunar Planet. Sci. XVII, 87, 1986). The essence of the hypothesis is that the secondary processing exhibited by these objects resulted from an episode of aerodynamic heating most plausibly attributed to entry into the atmosphere of a large planetisimal. Microprobe and SEM analyses performed this year indicate that "classic" chondrules and ferro-magnesium aggragataes in Allende may also have experienced thermal processing related to the growth processes of a parent body. Details are provided in the attached Appendix. Synthesis of this data, along with an evaluation of other heating mechanisms, are currently in progress. The implications of our conclusions with regard to the Allende parent body are that it was a large (~1,000 km radius) body possessing a substantial (but perhaps transient), dusty atmosphere.