THE RAPID DISSIPATION PHASE OF THE PRIMITIVE SOLAR NEBULA. A.G.W. Cameron, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138.

Recent work on the formation of stars from the dissipation of a disk (1) has shown that a uniform rate of accretion does not deposit sufficient energy in the outer envelope to allow a fit to the positions of T Tauri stars in the HR diagram after cessation of accretion. On the other hand, an accretion history in which the rate of accretion is proportional to the elapsed time does allow fitting the brightest observed T Tauri stars. In this relationship, the terminal rate of accretion is twice the mean rate of accretion over the accretion period. For the sun, an accretion interval of about 5 to 10 x 10^4 years is a reasonable dispersion in the interstellar infall time, meaning that a maximum accretion rate of 2 to 4 x 10^{-5} solar masses per year can be expected near the terminal stage of accumulation of the sun.

The basic theory of disk dissipation (2) determines the rates of transport of energy, angular momentum, and mass and the rate of local deposition of energy within the disk if the kinematic viscosity is known. For the last decade, in the absence of a physical theory of this viscosity, it has been the practice to parameterize the viscosity as a constant, "alpha", multiplied by the speed of sound at midplane and the scale height of the gas above midplane (3). Now a physical theory of alpha has been introduced which relates it to the conditions in a thermally convective region of the disk (4). Estimates by Canuto et al and by W. Cabot (unpublished) give alpha in the range 0.14 to 0.24, and I have adopted 0.24 as probably being the most reasonable value.

This new theory imposes new constraints on the way in which models of the primitive solar nebula must be constructed. The previous practice had been to assume that the local rate of energy deposition due to viscous dissipation had to be balanced by an equal rate of energy radiation from the same locality. However, it is now required that the interior of the disk be thermally convective, which means that everywhere there is a small superadiabatic gradient. In fact, it is a reasonable approximation to take all parts of the disk interior as having the same entropy. This means that there are strong constraints on the way in which a radiative layer can be attached to the convective zone at the surface, and in general the local radiation of energy will not be equal to the local deposition of energy. The new condition must be that the integral of the rate of energy deposition through the whole disk must be equal to the rate of radiation of energy from the whole disk plus the rate of change of the internal energy.

In the present study I have constructed simplified models of the inner part of the nebula, in the range 10^{12} to 10^{14} cm., subject to the assumption of a steady mass flow through the region and the presence at the center of a one solar mass sun. These conditions should be reasonable for the late stages of accretion of the sun. The models were constructed as follows. First, a general adiabat was determined for an arbitrary entropy, and this was used throughout the interior of the model. The vertical structure was computed at a point by integrating upward the structure equations using the adiabat, and reaching a radiative surface condition when the radiative flux computed along the temperature gradient became equal to the local radiation rate, provided the material between that point and the midplane had sufficient optical depth to sustain the radiation. The condition that the total rate of energy deposition should equal the total rate of energy radiation was applied only between the point of first condensation of iron and the point of first condensation of ice (at both of these points there is an abrupt change in the opacity). The midplane pressure at the starting radius for the model was adjusted until this condition was satisfied. It was then possible to determine the mass of the nebula segment, the rate of mass flow, and the corresponding characteristic dissipation time for the model.

The derived characteristics of four models produced in this way are shown in the table below. The above discussion on the disk dissipation time indicates that near the termination of the accretion the disk is likely to have properties intermediate between models A and B. However, if the dissipation should continue until the mass in the disk is drawn down to a small value, then models C and D may become of interest. Note, however, that their dissipation times have really become quite long. The mass in the disk less than a radius of 10^{14} cm is given; this mass scales approximately as the radius for the steady flow approximation, and probably does not deviate too much from this behavior until near the outer edge. Thus the total mass in the disk is likely to be an order of magnitude or so larger than given in the table below. Most solar nebula 'low mass models' claim there is likely to be a few per cent of a solar mass out to the orbit of Neptune, so the present considerations predict that the mass is larger by a moderate factor at the time of maximum dissipation. Model C has roughly the mass claimed by low mass models and may well be representative of the situation when the disk has declined from its period of maximum dissipation.

In the middle and late stages of accretion, the sun has a luminosity of the order of 20 to 30 times the present value (1). This energy is primarily radiated from the polar regions, since the equatorial regions form a continuous fluid link with the nebula. There is likely to be a great deal of low density gas and dust in the vicinity of the nebula, and the energy radiated from the sun, after scattering, can provide some heat for the outer parts of the nebula. In fact, the convection in the nebula must become less vigorous, and the dissipation time will go up, as the solar-maintained temperature in the outer layers of the nebula rises toward the value that the radiation of the internally-generated heat requires. Thus it can be expected that the high solar luminosity will gradually shut down the convection in the nebula and hence its dissipation. I call this the thermally-stabilized phase of the nebula. It may start from something like model C and cool off from there.

One point of particular interest for planet formation is that the interior temperatures in the nebula exceed the condensation temperature of iron to surprisingly large radii. For models A through D the radii at which iron condenses are, respectively, 2.5, 1.0, 0.54, and 0.28 astronomical units. Thus during the maximum dissipation stage of the nebula, small bodies will be totally evaporated to a distance beyond that of formation of Mars. Bodies of planetary size, such as remnant cores of condensed matter left over from the evaporation of giant gaseous protoplanets, may survive this period. In fact I postulate that Mercury obtained its unique composition by losing through evaporation the bulk of its original silicate mantle, since its environment attains a temperature of about 2400 K. Dust grains and dust balls can turbulently diffuse into this region only when convection is nearly shut down just before the thermal stabilization phase begins.

Only when convection has been fully shut down are the small particles, grains, dustballs, and chondrules and inclusions, free to settle through the gas to midplane. I assume, following Levy (5), that many of the dustballs have previously been melted into chondrules and inclusions through heating by nebula flares. Upon arrival near midplane, these solids can be collected together by gravitational instabilities into objects of asteroidal size, and they are then available for bringing some of the more volatile elements into the process of accumulation of the planets. The characteristic pressure governing the composition of the solids is likely to be of the general order of 10^{-5} bar.

MODEL CHARACTERISTICS

Model Number	Mass $R<10^{14}$ cm	Flux gm/sec	Dissipation time years
A	0.085	3.1×10^{21}	2.05×10^{4}
B	0.019	4.0×10^{20}	1.59×10^{5}
C	0.0058	7.1×10^{19}	9.00×10^{5}
D	0.0020	1.3×10^{19}	4.90×10^{6}

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