THE INTERACTION BETWEEN GIANT GASEOUS PROTOPLANETS AND THE PRIMITIVE SOLAR NEBULA

A. G. W. CAMERON
Harvard-Smithsonian Center for Astrophysics, Cambridge, Mass., U.S.A.

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Abstract. The manner in which a giant gaseous protoplanet becomes embedded in the primitive solar nebula determines surface boundary conditions which must be used in studying the evolution of such objects. On the one hand, if the system resembles a contact binary system, then the envelope of the protoplanet should approach the entropy of the surrounding nebula. On the other hand angular momentum transfer by resonance and tidal effects between the nebula and the protoplanet may cause the nebula to exhibit a zone of avoidance near the protoplanet, thus inhibiting exchange of material. This problem has been studied with a computer program developed by D. N. C. Lin which simulates disk hydrodynamics by particle motions with dissipation. These studies suggest that for expected values of the protoplanet/protosun mass ratios, significant inhibition of mass exchange is likely, so that it is a reasonable next step to undertake protoplanet evolution studies with the imposition of minimum protoplanet surface temperatures.

1. Introduction

In applying the theory of a viscous accretion disk (Lynden-Bell and Pringle, 1974) to study the behavior of the primitive solar nebula, one of the main conclusions which I reached was that the nebula should have become repeatedly unstable against axisymmetric perturbations to form ring-like condensations (Cameron, 1978). Such gravitational condensations are then expected to break up into giant gaseous protoplanets, many of which will merge together by collision. It seems necessary to understand in some detail the evolution of such giant gaseous protoplanets in order to make further studies of the behavior of the primitive solar nebula, since it appears that these protoplanets will affect that behavior in a major way. A first step in this direction was the recent study of the structure and evolution of isolated giant gaseous protoplanets (DeCampli and Cameron, 1979). In this study the protoplanets were treated as if they were stellar structures, that is, spheres of hot gas in hydrostatic equilibrium radiating into a vacuum. It was recognized at the time that this isolated boundary condition would be very unrealistic, but it was felt to be a useful condition for a preliminary reconnaissance of the problem.

Before the next step can be taken, it is necessary to understand what happens when a giant gaseous protoplanet is embedded in the primitive solar nebula and an exchange of gas can take place between the two systems. In one extreme, if gas exchange is supposed to take place readily and extensively between the two systems, then the situation may resemble that of a contact binary star system. In such systems the two stellar components become embedded in a common envelope of gas. Hazlehurst and Refsdal (1978) have

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argued that in such circumstances, where transport time scales are much shorter than thermal time scales, it is not possible to have an entropy discontinuity between the two systems, but rather the entropy of both stellar envelopes must approach the same value. In the case of the primitive solar nebula and giant gaseous protoplanets, distances are large and temperatures and velocities are small. Thus, unless there can be particularly vigorous exchange of material between the primitive solar nebula and the protoplanet, the currents of gas will not be able to move rapidly enough over the surface of the protoplanet compared to characteristic cooling times, so that it is doubtful that isentropic conditions can be maintained. Therefore one of the purposes of the present study was to determine the likelihood of a very rapid mass exchange.

On the other hand, recent studies of the behavior of gaseous disks formed by Roche lobe overflow of gas from a secondary component to a primary component in a binary system have shown that the resulting disk exhibits a very different kind of behavior. Such a disk tends to be relatively thin and pressure gradient effects on the fluid modify only relatively slightly the motions compared to those which the gas would have if composed of noninteracting orbiting particles. Given that such gases are subject to some kind of viscous dissipation, a series of papers (Lin and Pringle, 1976; Papaloizou and Pringle, 1977; Lin and Papaloizou, 1979) has shown that resonance and tidal interaction effects provide torques with resultant angular momentum transfer between the secondary component of the binary and the disk. If the inverse mass ratio of the components is smaller than the effective Reynolds number of disk, then the disk is truncated between the two components. The flow of angular momentum results from viscous dissipation in the inner portion of the disk, close to the primary component, but in the outer portion of the disk, angular momentum flows by tidal interaction into the orbital motion of the secondary component. Under these circumstances there is a zone of avoidance of the gas in the disk around the secondary component and there is a strong inhibition of mass exchange between the two components (apart from mass overflow effects from the secondary to the primary). If this condition should also apply in the case of an embedded giant gaseous protoplanet within the primitive solar nebula, then mass exchange between the systems could not govern the surface condition, but instead a more likely surface condition would be the maintenance of a minimum surface temperature by the protoplanet owing to the thermal bath from the surrounding primitive solar nebula in which the embedding occurs.

2. Procedure

This problem has been investigated using a method of particle representation of fluid dynamics described by Lin and Pringle (1976). I am greatly indebted to Dr. D. N. C. Lin for furnishing me a copy of his computer code.

The essence of the procedure is as follows. A fluid is represented by the motion of a fairly large number of particles. This motion is confined to two dimensions. The space occupied by the particles is divided into a large number of discrete boxes. In each time step, the motion of the individual particles is followed by numerical integration, the particles responding to the forces from the primary and secondary components of the system. At the end of each time step, the particles in each of the boxes are subjected to dissipation. Within each box, the particles are required to rotate rigidly around their common center of mass. This process conserves momenta but dissipates energy. Lin and Pringle (1976) and Lin and Papaloizou (1979) have shown that this procedure appears to reproduce well many of the phenomena which are inferred about the behavior of gas streams and disks in close binary systems.

Dr Lin has incorporated an additional feature into his computer code which was utilized in this investigation. This is a partial feedback of the dissipation energy within each box into random motions of the particles. This has to be done in such a way that momenta remain conserved. The technique is therefore to divide the particle population of a box into pairs plus, if necessary, a triplet, and to introduce the energy which is fed back into the system in the form of 'breathing' motions of the particles relative to the ceters of mass within these pairs and triplets.

In my evolutionary studies of the primitive solar nebula, I found that the disk became unstable against the formation of protoplanets at a very early stage, before very much mass had accumulated at the center. The mass of a giant gaseous protoplanet is expected to be of the general order of magnitude of a Jupiter mass (DeCampli and Cameron, 1979) and the mass at the center of the primitive solar nebula at the time of formation of giant gaseous protoplanets is expected to be only a few percent of a solar mass. It follows that the mass of the protoplanet would probably have been between one and ten percent of the mass of the protosun at the time of formation of the protoplanet. The inverse of this mass ratio is indeed expected to be smaller than the Reynolds number of the turbulence in the primitive solar nebula. Therefore the investigations were carried out for secondary/primary mass ratios of 0.01 and 0.1.

3. Results

For each of these two mass ratios, three cases were computed, corresponding to 0, 0.2, and 0.5 of the dissipation energy within the disk being fed back into random motions of the particles. The initial condition consisted of the establishment of 2379 particles with a uniform surface density in orbits, originally circular, about the primary mass, with the superposition of a small random velocity component, and extending both inwards and outwards from the secondary mass.

The basic time step in the integration of the equations of motion was 0.01 of the time required for the secondary to move one radian around the primary. After each time step the particles were allowed to interact within boxes to dissipate energy. 2500 boxes were used, covering an area of 16 square units, where a unit is the distance between the primary and secondary masses. The computer code utilizes a rotating coordinate system in which the primary and secondary masses remain stationary. The system was allowed to evolve for five rotations of the secondary mass about the primary mass, so that the motion

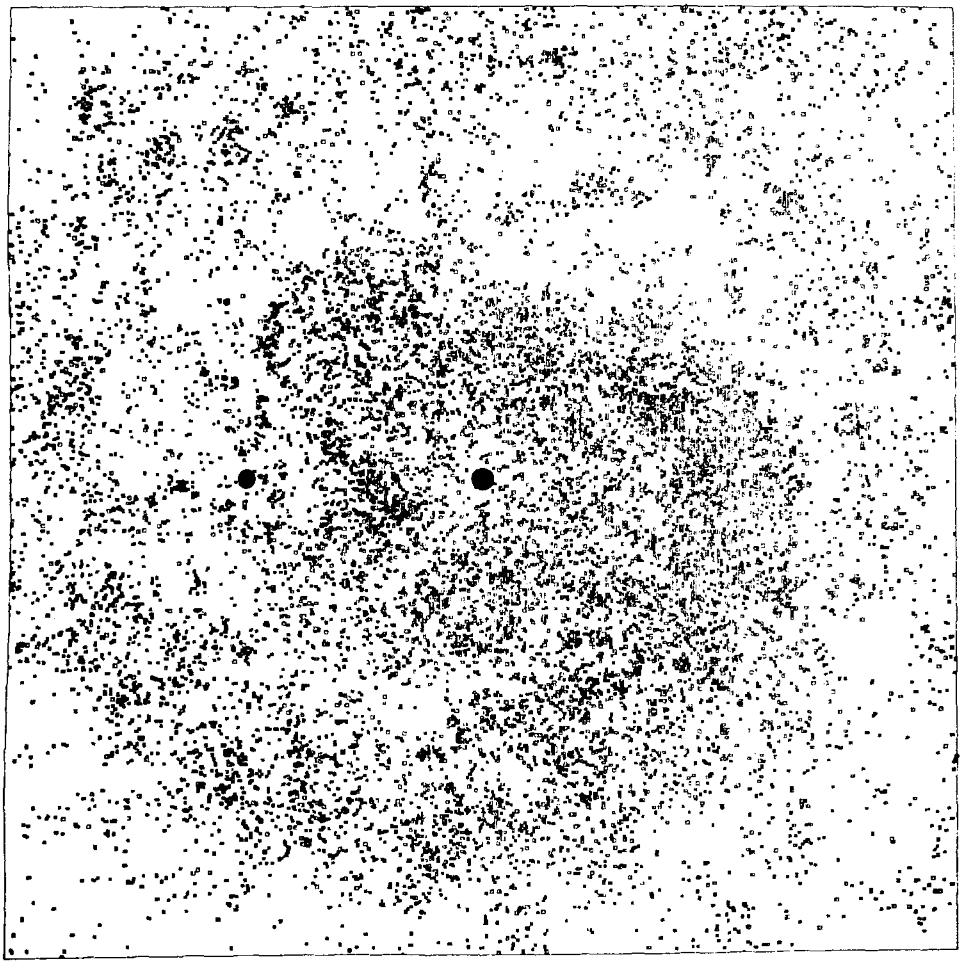

Fig. 1. Case $q = 0.01$, energy feedback $= 0$. The primary mass is at the center and the secondary mass is half-way between the center and the left-hand edge.

of the particles had time to settle into a pattern. This was a compromise between the short time scale on which transients disappear and the long time scale on which dissipation greatly depletes the particles. Over the next two rotation periods, the positions of the particles were plotted at regular intervals. The results for the six cases are shown as Figure 1 through 6 of this paper. In each of these figures the primary mass is located at the center and the secondary mass is located half-way between the center and the left-hand edge of the figure.

Figure 1 shows the results for a reduced ratio, q, of 0.01, with no energy fed back from the dissipation into random motions of the particles. It may be seen in this figure that indeed a 'zone of avoidance' has opened up around the secondary mass, but the pattern is not a simple one and there is not a circular truncation of the inner disk surrounding the primary. In fact, there is a strong distortion in the particle motions, with the appearance of a prominent spiral pattern at the bottom and lower left of the figure and the possibility of a weaker spiral pattern at the top and upper right of the figure. Lin and Papaloizou (1979) have discussed spiral patterns in the motion of the fluid that are likely to develop in association with the 2:1 resonance between the fluid motions and the motion of the secondary mass. However, the spiral pattern found by Lin and Papaloizou is confined within the Roche lobe of the primary, whereas the spiral pattern which appears to be present here extends over a larger radial distance. Dr Lin has suggested that particle outflow is occurring through the L3 point; I have not pursued the issue of this spiral pattern, although it is clear that it forms an interesting physical phenomenon.

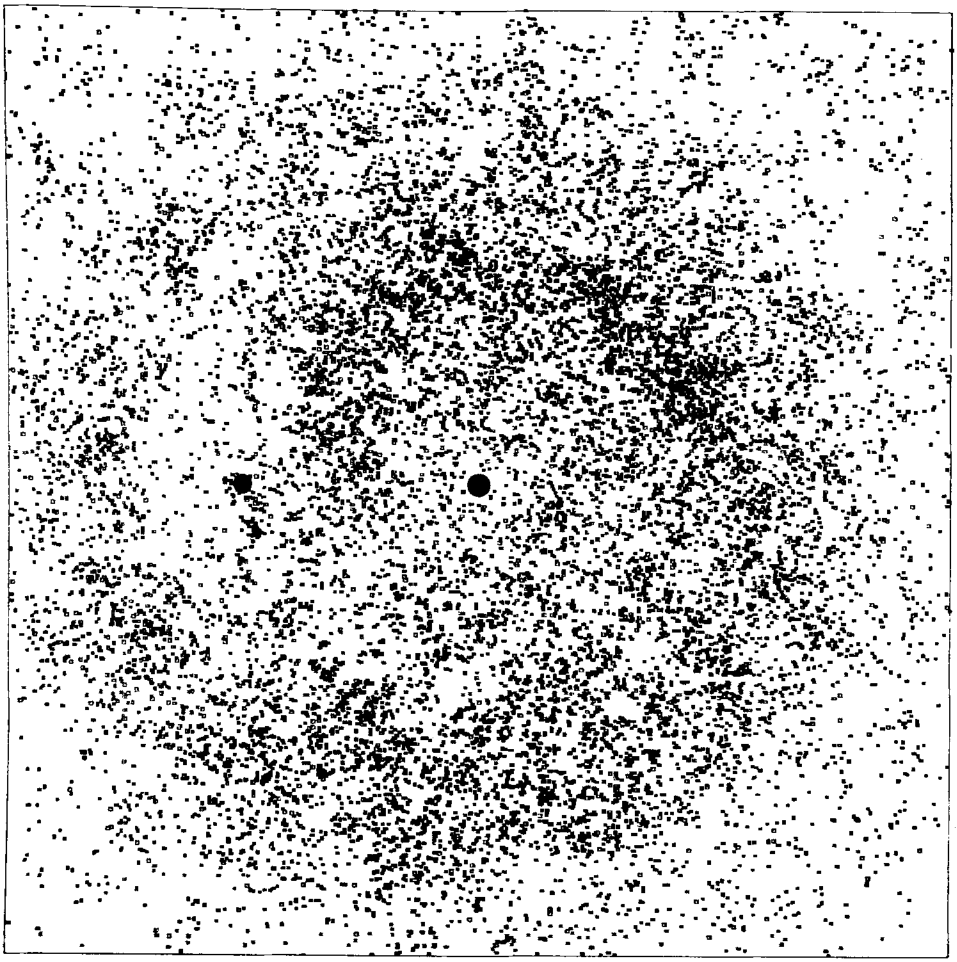

Fig. 2. Case $q = 0.01$, energy feedback $= 0.2$.

Figure 2 is also for $q = 0.01$, but with 0.2 of the dissipation energy fed back into random motions of the particles. It may be noted that many features of the pattern shown here are similar to those of Figure 1, except that there are more particles in a radial distance somewhat larger than the separation between the secondary and the primary components, and the pattern of Figure 1 is somewhat smeared out. However, there is still a significant zone of avoidance about the secondary mass.

In Figure 3 is shown the case for $q = 0.01$ and with a feedback of 0.5 of the dissipation energy into random motion of the particles. Here it may be seen that most of the characteristic features of the patterns of Figures 1 and 2 have completely smeared out. The zone of avoidance about the secondary mass has largely disappeared.

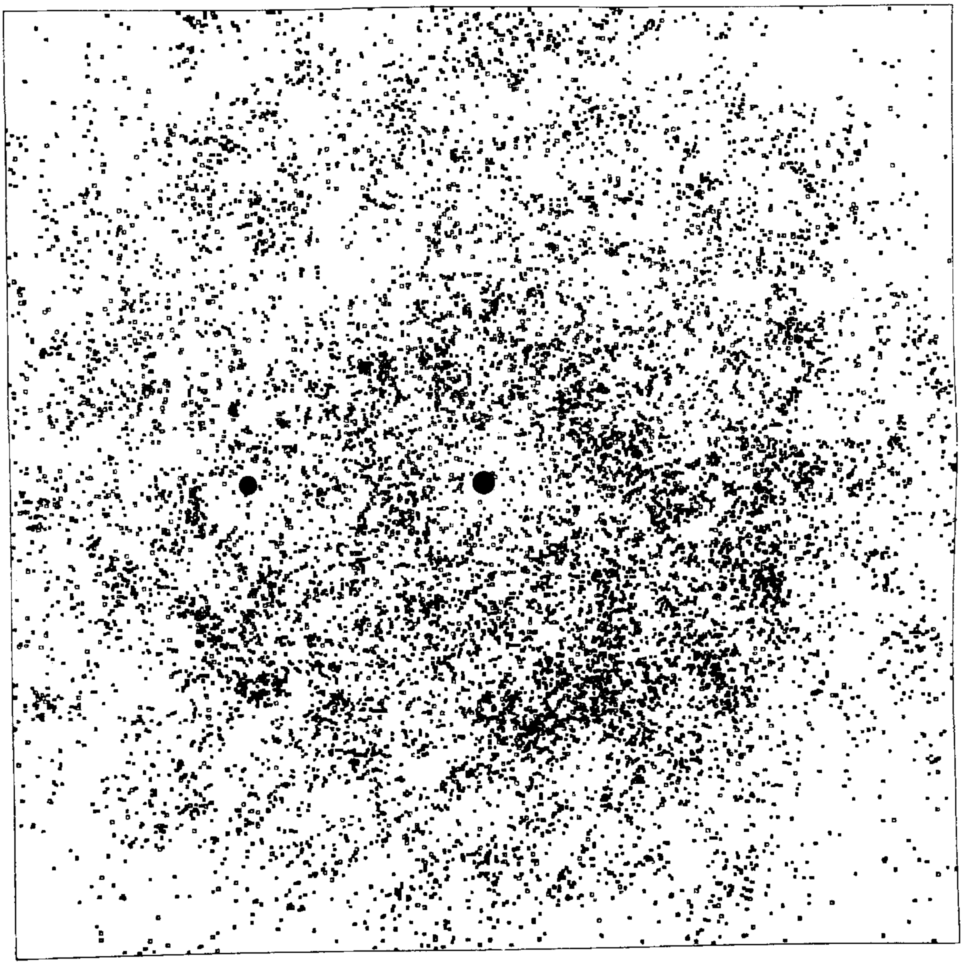

Fig. 3. Case $q = 0.01$, energy feedback = 0.5.

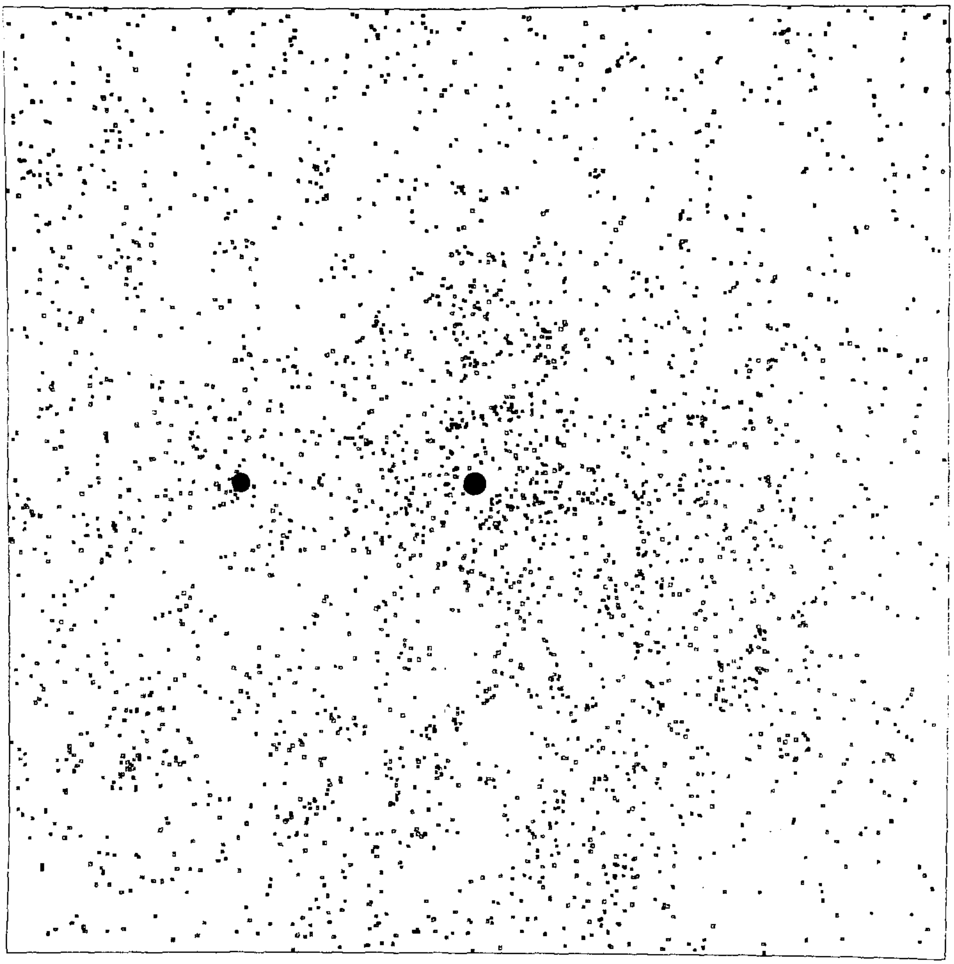

Fig. 4. Case $q = 0.1$, energy feedback = 0.

Figure 4 shows the case $q = 0.1$ with no feedback of dissipation energy. It may be noted that the particle densities have very greatly declined from those that were evident in the preceding figures. In fact, this decline of the particle densities has gone sufficiently far that the conditions needed for the particle motions to represent fluid motions have broken down. The particle population in the interaction boxes within the system is now so low that particles are subject to dissipation in only a small number of their time steps. Because of this, and because of the large perturbations due to the more massive secondary body, the motions of the particles have become more random and there is no 'zone of avoidance' evident about the secondary mass. However, this should be viewed in the light of the fact that something of a zone of avoidance has pervaded the entire figure. Normally about 440 of the particles collect in the primary mass as a result of viscous

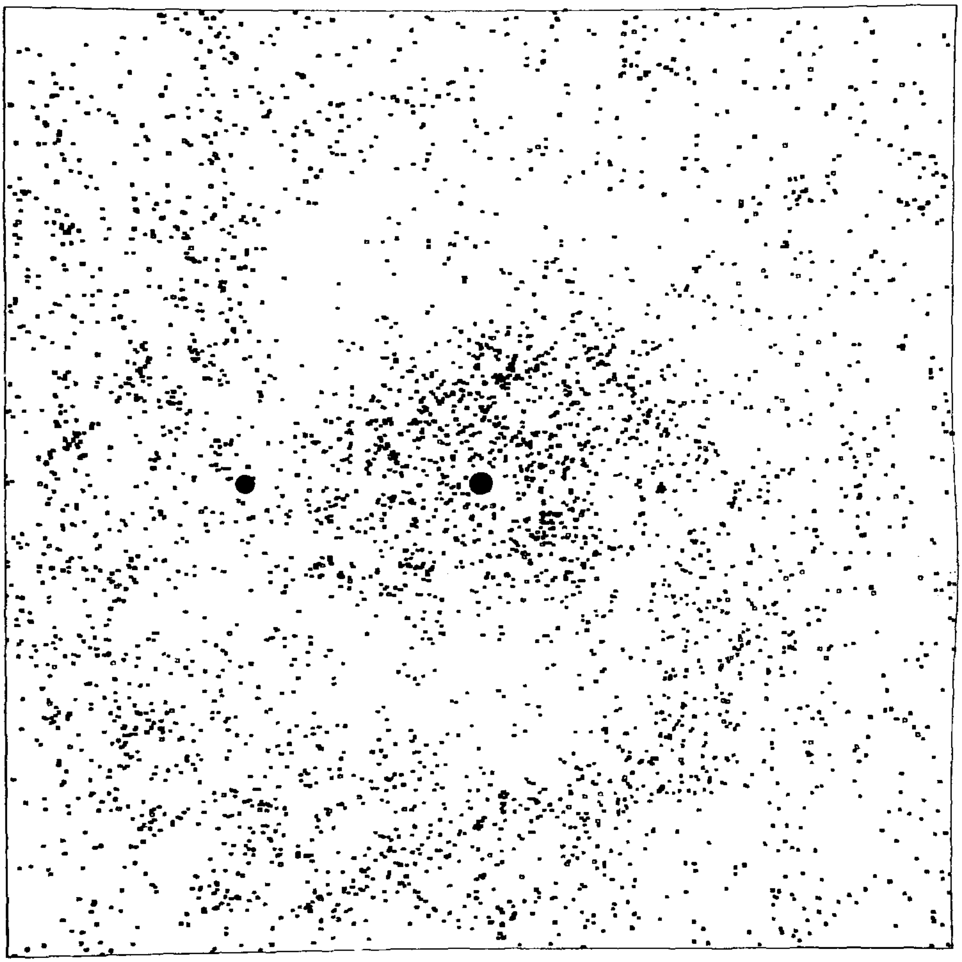

Fig. 5. Case $q = 0.1$, energy feedback = 0.2.

dissipation within the disk surrounding the primary, but in this case that number has gone up by 50%. Most of the rest of the missing particles have been ejected beyond the boundary of this diagram.

In Figure 5 the situation is shown for the case $q = 0.1$ and with 0.2 of the dissipation energy fed back into random motions. In this case it may be noted that the particle population has declined much less so that the particle representation of fluid dynamics is somewhat more valid. Now there is quite evidently a zone of avoidance in a ring around the primary at the distance of the secondary mass. There is no evidence of a spiral pattern, nor, according to Lin and Papaloizou (1979), is one to be expected. In this case there was only a mild increase in the number of particles accreted by the primary; once again the considerable diminution of the original particle density has resulted from ejections beyond the borders of the diagram.

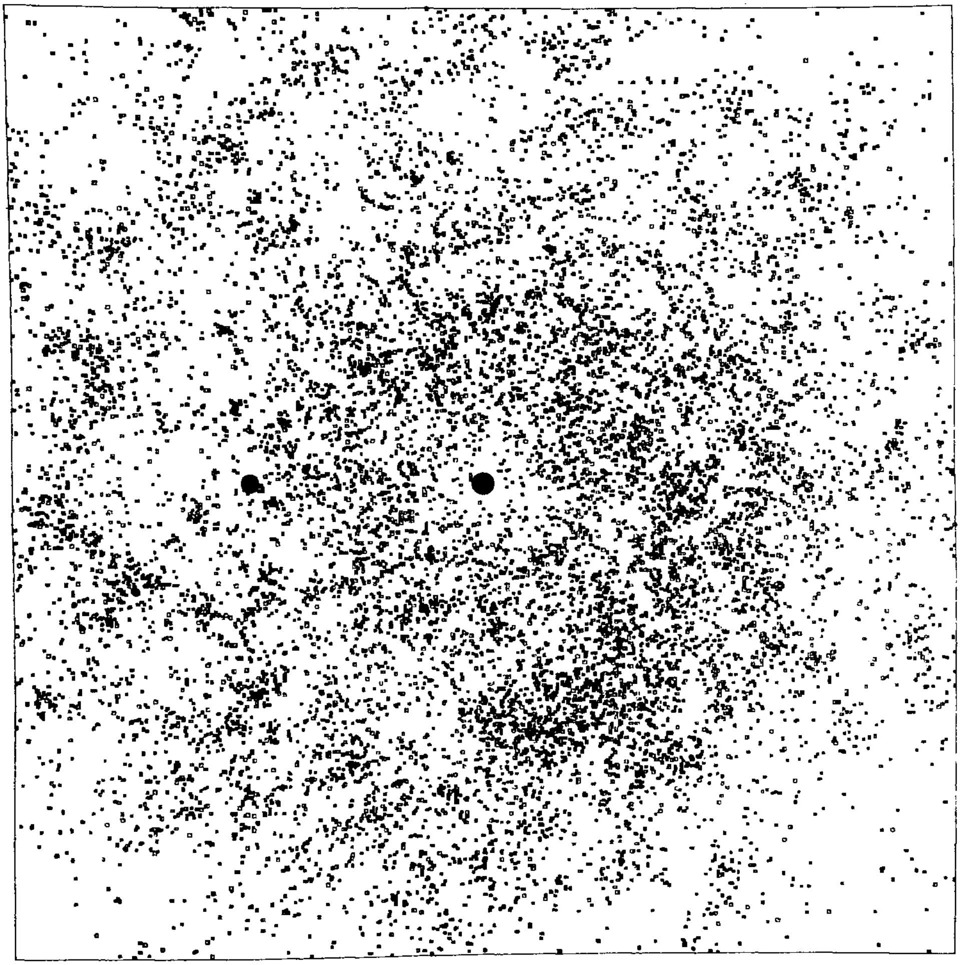

Fig. 6. Case $q = 0.1$, energy feedback = 0.5.

Finally, in Figure 6, are shown the results of the case $q = 0.1$ with 0.5 of the dissipation energy fed back into random motions. Here the zone of avoidance around the secondary mass has nearly disappeared and there has been relatively little diminution of the original particle densities.

4. Discussion

From these results it is clear that if no significant amount of the dissipation energy is fed back into particle motions, then very significant zones of avoidance develop around the secondary mass for mass ratios in the range of interest to the giant gaseous protoplanet problem. As dissipation energy is fed back, however, the zones of avoidance narrow and tend to disappear.

The feeding of energy into random particle motions is equivalent to adding pressure effects to the general motions of the gas (D. N. C. Lin, personal communication). However, because of the rather large mean free paths of the particles in the present problem, the pressure effect should here be considered to be essentially a turbulent pressure effect. It is reasonable to ask whether such an effect should be expected in the primitive solar nebula.

I have argued (Cameron, 1978) that one of the main driving forces which should induce vigorous turbulence within the primitive solar nebula is the presence of vigorous meridional circulation currents within the disk. Such currents arise because of the impossibility of arranging to have the gravitational potential, pressure, temperature, and density of the gas all constant on the same level surface in a rotating system. However, there must be present a significant luminous flux in order for the meridional circulation currents to flow. This luminous flux arises from the local dissipation that accompanies the viscous transport of mass, energy, and angular momentum within the disk. It is expected that such large motions in a system of high Reynolds number will become highly turbulent. In this sense it is indeed reasonable to anticipate that some of the energy locally dissipated will be fed back into turbulent pressure. However, the theory of meridional circulation currents has not been developed for a highly flattened rotating system, and the rate of generation of turbulent pressure by such currents is also very uncertain.

This means that a clear-cut answer to the problem posed has not been achieved. However, from the work of Lin and Papaloizou (1979), it appears that the transfer of angular momentum into orbital motion of the secondary mass is likely to be a highly effective process in the outer part of the inner disk, exceeding the internal viscous transport effects there, and as long as this is a significant process in the evolution of the disk, then it is unlikely that the dissipation energy feedback can become so important as effectively to obliterate all effects of the zone of avoidance about the secondary mass. Therefore it appears that, even though significant rates of mass exchange between the protoplanet and the nebula are possible, it is likely that a significant entropy discontinuity can exist between the two systems.

Under these circumstances, it seems prudent to take as the next step in the investigation in the evolution of giant gaseous protoplanets, the imposition of a minimum surface temperature on such models, corresponding to the immersion of the protoplanet in the thermal bath that accompanies the surrounding primitive solar nebula, with mass exchange effects being unlikely to exert thermodynamic control on the surface boundary conditions.

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