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The Pre-Hayashi Phase of Stellar Evolution

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Abstract

The structure and evolution of protostellar disks ("stellisks") are being studied. These are flattened fragments of a collapsed interstellar cloud. Their angular momentum properties are those appropriate to uniformly rotating spheres of variable density distribution. Corresponding to each angular momentum distribution there are two separate density distributions in which there is centrifugal equilibrium in the disk. One distribution is very flat, rotates approximately uniformly, and probably deforms into a close binary pair. The other is axially condensed and is the probable precursor of single stars and planetary systems. In stellisks of the latter kind with lower densities near the rim, one or a few separate rings form near the outer edge. Since stellisks are formed as a result of a dynamical collapse process, they have an initial stage of short-lived turbulence. This transports angular momentum outwards and increases the tendency for formation of outer rings. The structure perpendicular to the plane of the disk has also

been studied. The disk cools and contracts at constant central pressure. For central temperatures $\leqslant 10^3$ $^{\circ}$K, the disk has thermally-driven convection in the regions with surface densities $\geqslant 10^5$ gm./cm.^{2}. The resulting turbulent viscosity causes mass inflow to form a central star on the lower part of the Hayashi track. Such a star will be in the T Tauri phase and a strong stellar wind will blow away the low density gas in the remainder of the disk. It is probable that an axially condensed stellisk with low surface densities cannot form a star. It is suggested that the unseen mass in the solar neighborhood consists largely of permanent stellisks which have negligible surface temperature but whose presence may be inferred from stellar occultations.

Some time ago I presented an analysis of the conditions in which an ordinary interstellar cloud could become unstable against gravitational collapse (Cameron 1962). For a cloud of 10^3 $M_{\odot}$, an initial density of $\sim 10^3$ particles/cm.^{3} is required. High initial densities of this kind may be produced if the outer regions of an HI cloud are ionized by an O or B star, thus creating the necessary high surface pressure for the compression to high density. The gas must be predominantly compressed along the magnetic lines of force in order that the enhanced magnetic pressure should not halt the compression. In the subsequent collapse the magnetic field should not play an important dynamical role (Cameron 1962, Pneuman and Mitchell 1965).

It is to be expected that the resulting cloud will be turbulent and that the collapse will be roughly isothermal. The resulting density fluctuations should initiate fragmentation in the cloud. In a recent paper I concluded that the turbulent component of the internal angular momentum of a fragment should be comparable to that associated with an initial corotation of the interstellar cloud with its orbital motion about the center of the galaxy (Cameron 1968).

The spherical collapse of a protostar would form an object on the Hayashi track in the H-R diagram. However, considerations of the conservation of angular momentum in the collapsing fragment indicate that it should form a rotating flat disk with a radius of several tens of astronomical units, much larger than a star would possess on the Hayashi track (Cameron 1962, 1963). It has been the objective of the present work to discover how such a disk might dissipate to form a more compact star on the Hayashi track.

In order to relate the problem to the interstellar cloud conditions, the cloud fragments were assumed to be uniformly-rotating spheres. The equators of these spheres were assumed to have conserved their local angular momentum from the initial cloud corotation condition with its angular velocity of 10^{-15} radians/second. The density was assumed to vary linearly with radius from a central value to a surface value. The specific models used in the present calculations have two solar masses. In one sphere the density was uniform ("uniform sphere") and in the other sphere the density fell linearly from the central value to zero at the surface ("linear sphere").

Each sphere was divided into 50 cylindrical zones concentric about the axis of rotation, and the mass and angular momentum of each zone was calculated. The mass was then considered to have collapsed into a thin flat disk, and it was required that the mass in the disk be everywhere in centrifugal equilibrium with respect to the gravitational forces at that point in the disk. Radial pressure gradients were neglected since I was interested in the case in which thermal energies in the gas would be much less than the bulk rotational kinetic energies.

Gravitational potentials were calculated by the technique of a superposition of concentric spheroidal shells of varying density in the limit of zero eccentricity (Burbidge, Burbidge, and Prendergast 1960 a, b; Brandt 1960; Brandt and Belton 1962; Mestel 1963). With some trial mass distribution in the disk, the surface density in each zone was varied and the changes in angular momentum per unit mass required for circular motion for all the other zones were determined. A matrix was then inverted to determine what perturbations to introduce into the surface densities of all the zones so that the angular momentum required for circular motion in the model would approach the assigned values. The problem is highly non-linear and convergence to the centrifugal equilibrium condition is very slow. It would be helpful to develop improved mathematical techniques which would lead to faster convergence.

After the above technique had been developed, it was discovered that each of the two original spheres had two different surface density distributions for which it was in centrifugal equilibrium. The four solutions are shown in Figure 1. The flat solution for the uniform sphere is known classically (McMillan 1958); it is in uniform rotation.

In addition there is an axially-condensed solution. Mestel (1963) has discussed such axially-condensed solutions which he shows can be produced by slight perturbations in the mass distribution of a uniform sphere. However, it has been shown by the present numerical techniques that the same mass and angular momentum distribution is consistent with each solution. In the axially-condensed solution the angular velocity varies roughly inversely as the radial distance, so that there is a large amount of shear in the solution.

The flattened linear sphere exhibits a similar behavior, as shown in Figure 1. There is a nearly-flat solution, which is nearly in uniform rotation, and which has a very sharp edge. The axially-condensed solution is more strikingly so. The irregularity of this solution near the axis is an artifact of the finite zoning and has no physical significance. This solution also has a condensed ring near the outer edge, which will be discussed in more detail below.

I believe that the existence of these two solutions has great cosmogonic significance. Hunter (1963) has examined the stability of the classical uniformly-rotating flat disk. He has found it to be unstable against both radial and non-radial perturbations. (Professor Gold has informed me that he and Bondi have found a very limited range of parameters in which this appears not to be true.) K.H. Prendergast (private communication) has shown numerically that a flat galactic disk with superposed random velocities of the individual mass points deforms into a corotating bar. It appears likely that the corotating disk will deform in a similar manner and will subsequently form a close pair of binary stars. No further calculations have been carried out with these flat solutions. Whether a collapsing interstellar cloud fragment forms a flat disk or an axially-condensed disk must depend upon subtle features of the dynamics of the collapse.

I refer to the axially-condensed protostellar disks as "stellisks". I assume that they are stable against perturbations, but no analysis of this point has been made, and one is badly needed.

When a stellisk is formed as a result of the dynamical collapse process, the gas will overshoot the position of centrifugal equilibrium, thus inducing a state of initial turbulence in the disk. The energy input into the turbulence arises from the released gravitational potential energy. Since there is no continuing source of energy input into the turbulence, it is short-lived. The largest eddy motions are broken into smaller motions after the gas has moved through a mixing length, which takes a small fraction of an orbital period.

I have estimated the angular momentum transfer between adjacent zones due to turbulent viscosity, using data appropriate to the stellisk models of Figure 1. It turned out that the angular momentum transfer would be sufficient to make adjacent zones corotate if they did not change their radial positions. In fact, the angular momentum transfer would spread the zones apart and increase the shear between them. The situation was treated very crudely by taking the inner five zones for a stellisk model and redistributing the angular momentum so that they would corotate at their given positions. This procedure was then applied to zones 2 to 6, 3 to 7, and so on in the model until the outer edge was reached. The models were then again relaxed to centrifugal equilibrium.

The justification for this procedure lies in the fact that the center of a cloud fragment will collapse faster than the surface layers, so that the turbulent redistribution of angular momentum will be completed near the center before the outer parts have finished collapsing.

The model of the uniform sphere stellisk after dissipation of initial turbulence is shown in Figure 2; it is compared in the figure with the initial model of Figure 1. It may be seen that a slight further net central condensation of mass has occurred, except near the outer edge. A prominent outer condensed ring has formed, and a slight second ring-like perturbation is also present.

A similar behavior for the linear sphere is shown in Figure 3. In this case two prominent condensed outer rings are present.

It may be deduced from these figures that condensed rings will have an increasing tendency to form as the relative mass fraction in the outer layers is reduced and as the gradient of the angular momentum per unit mass in the outer layers is increased. The reality of the rings was tested by compressing and smoothing the outer zones of the linear sphere stellisk and relaxing again to centrifugal equilibrium. Again the two condensed rings appeared, but the outer one centered on a different zone. Thus the reality of the ring structure was demonstrated, but the uniqueness of the structure remains an open question.

Calculations with a finer zoning mesh are needed for a further investigation of this question.

It seems likely to me that these rings will be unstable against non-radial perturbations, and that they will deform to form separate disk-like condensations orbiting about the central disk. Such sub-disks seem likely precursors of the giant planets of the solar system.

The collapse of the interstellar cloud fragment will, in the late stages, lead to adiabatic heating of the inner parts of the stellisk to 10^4 ^{o}K or higher. There will be an initial period of rapid radiative cooling. Further dissipation of the disk will depend on the operation of turbulent viscosity to transport angular momentum outwards. The only apparent energy input source for such turbulence would be thermally-driven convection. This would require superadiabatic temperature gradients to exist perpendicular to the plane of the disk. Hence the structure of the disk perpendicular to the plane was investigated with the simplifying assumption that any column of the disk could be considered part of an infinite plane of matter having the same local conditions.

The structure of an isothermal column of this kind is well known (see for example Mestel 1963). The central pressure of such a column is proportional to the square of the surface density and is independent of the temperature. The height of such a column is proportional to the temperature and inversely proportional to the surface density. A more realistic column will not be isothermal owing to the presence of internal opacity, but the above relations are always at least approximately true.

At temperatures in the general vicinity of 3000 ^{o}K the opacity of stellar material is very low and no convection should be present. It is worth noting in passing that at 3000 ^{o}K about 10^{-3} of the mass will be in the form of OH under conditions of statistical equilibrium. Because of the low opacity there is no assurance of good interaction between radiation and matter, and it is an interesting hypothesis that population inversions in the OH molecule may be possible. P.M. Solomon and I are currently considering the question of whether this may be a suitable model for the maser-amplified OH emission from the compact galactic OH sources.

Below 2000^{o}K the opacity becomes larger due to the presence of condensed solids and H_2O, NH_3, and CH_4 molecules. The solids are mainly particles of metallic iron and magnesium silicate. Electron microprobe measurements of the structure of very primitive meteorites indicate metal and silicate particle sizes in the submicron range (E. Anders, private communication). These sizes are small compared to thermal wavelengths and allow Rosseland mean opacities to be calculated with negligible dependence on particle size. With opacities based on the particles alone, I have found that the surface density threshold for vertical convection lies between 10^5 and 10^6 gm./cm.^{2}.

I am currently putting in the additional effects of molecular opacities. Such opacity contributions depend on both pressure and temperature. My rough guess is that the threshold for vertical convection will be lowered to between 10^4 and 10^5 gm./cm.^{2}.

It may be seen in Figures 2 and 3 that surface densities in the stellisks lie above $10^{4.5}$ gm./cm.^{2} out to distances of several astronomical units (approaching 10^{14}cm.). Hence these inner parts of the stellisks will be subject to dissipation via turbulent viscosity once the disks have cooled to $\sim 10^3$ $^{\circ}$K. This will lead to an inward flow of mass and an outward flow of angular momentum. Hence a good fraction ($\sim 1\ M_{\odot}$ in the present models) of mass will flow in to form a star on the Hayashi track.

This mass flow will carry with it all finely divided solid material. In fact, all material of less than planetary size will be carried inward into the star. The inner planets represent only $\sim 10^{-2}$ of the condensed solids that would be present. Hence the rapid dissipation of the disk limits the growth of the inner planets.

After the central star has formed, it will be in the T Tauri phase, emitting an extremely strong stellar wind, presumably due to a hot corona excited by the turbulent motions in the fully-convective Hayashi phase. This will sweep away the primitive atmospheres which were captured by the inner planets from the stellisk gases, and also it will sweep away the thinner gases remaining in the outer nonconvective part of the stellisk. During the early part of this T Tauri phase a great deal of dust will remain in the environment, which will thermalize much of the radiation of the central star, producing a secondary peak of infrared radiation in the spectrum of the star.

The general features of the architecture of the solar system appear to emerge from the above analysis. Detailed agreement is not to be expected owing to the arbitrary initial density distributions assumed.

It was indicated at the beginning that there should be a considerable spread in the total angular momentum per unit mass of these stellisks. For a given mass, the surface density varies inversely as the fourth power of the total angular momentum. Thus we should expect that if the angular momentum is increased by only a factor 4 or 5, the surface density will become too small for thermally-driven convection to exist. Such stellisks probably cannot form stars except via the impossibly long process of dissipation by molecular viscosity. They are probably permanent. I wish to suggest that a good portion of the unseen one-third of the mass density in the solar neighborhood may consist of such stellisks.

It should also be noted that the first generation of stars to form in our galaxy presumably contained a negligible content of elements heavier than helium. Hence they would always have low opacity, and they could not form stars unless they were massive and compact. This may indicate that there is a lot of mass spherically distributed in the galaxy in the form of permanent stellisks.

Fleischer and Conti (1955) examined Palomar Sky Survey prints and concluded that there is a large number of small dark gaps in the star distribution in crowded regions of the Milky Way. They attribute these to dark "globules." If these have the average properties of Bok's globules, then they have a space density of 0.03 per cubic parsec, which is to be compared with a star density of 0.1 stars per cubic parsec. Although their conclusions were highly tentative, I regard them as permissive with respect to the above hypothesis. It is clear that further studies of this sort are greatly needed.

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Figure Captions

Figure 1. Surface density distributions for centrifugal equilibrium of disks formed from collapse of uniform and linear spheres.

Figure 2. Changes in surface density distributions in the uniform sphere stellisk after dissipation of initial turbulence.

Figure 3. Changes in surface density distributions in the linear sphere stellisk after dissipation of initial turbulence.

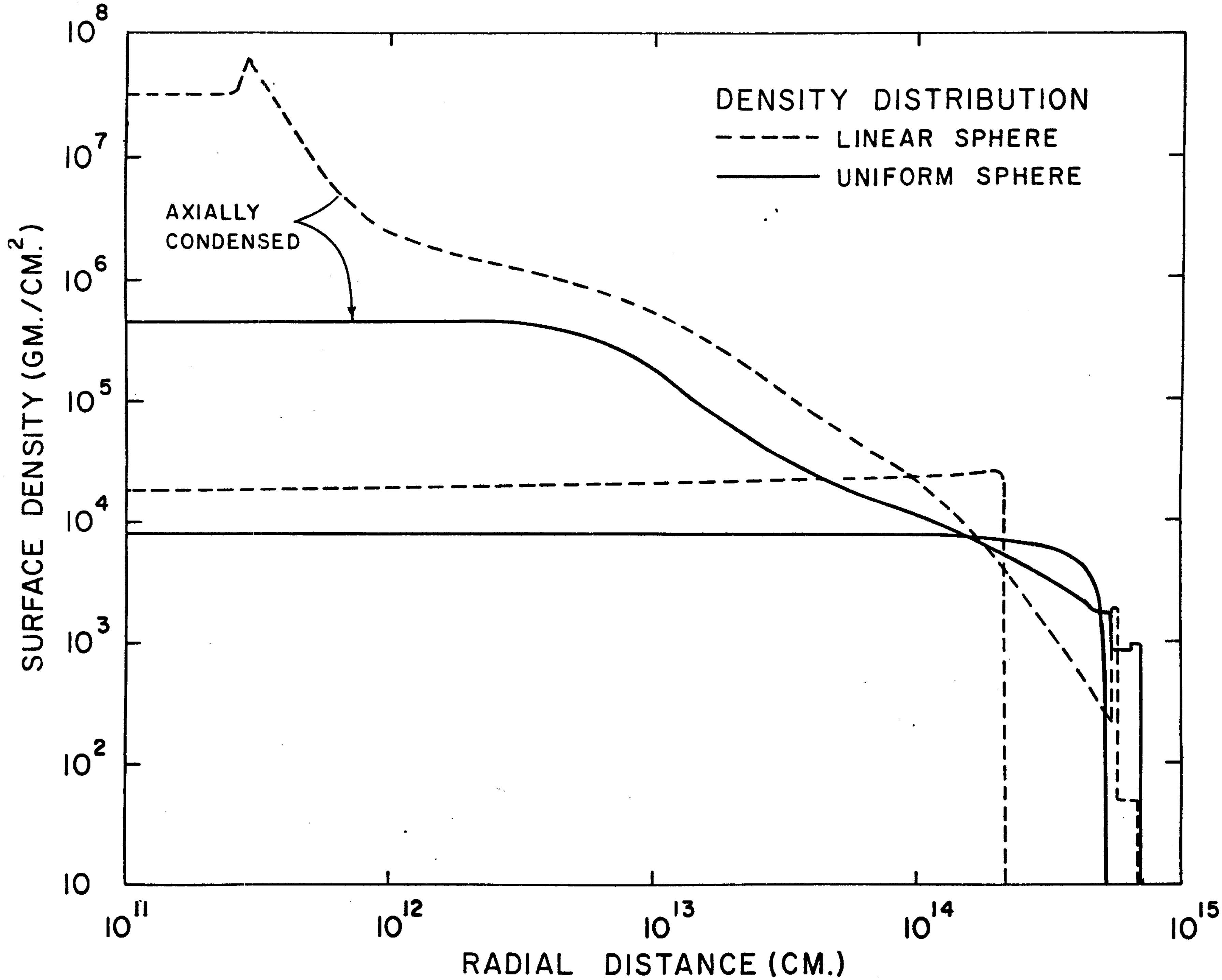
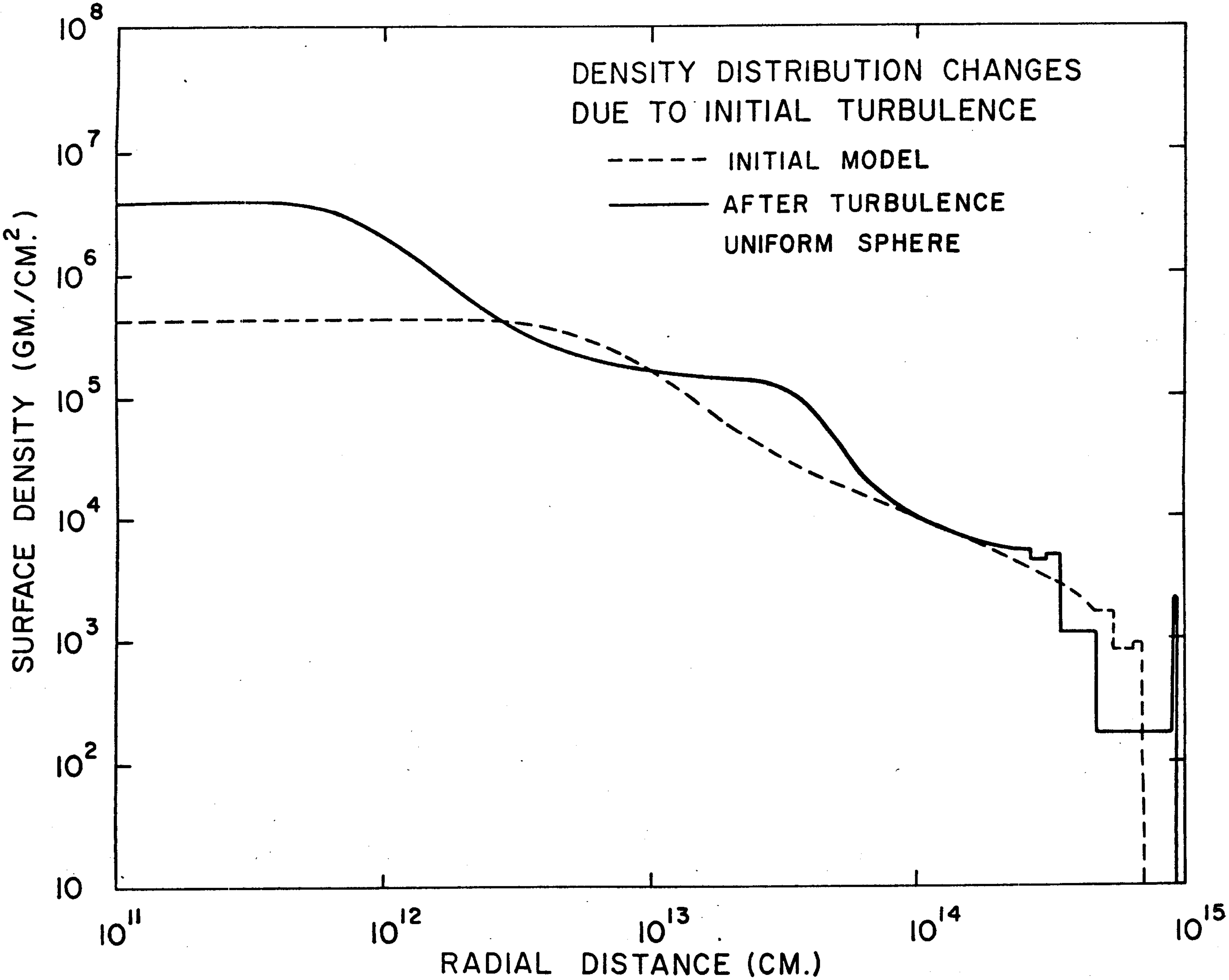

DENSITY DISTRIBUTION
LINEAR SPHERE
UNIFORM SPHERE
AXIALLY CONDENSED
SURFACE DENSITY (GM./CM.^{2})
RADIAL DISTANCE (CM.)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}

Figure 1


DENSITY DISTRIBUTION CHANGES
DUE TO INITIAL TURBULENCE
INITIAL MODEL
AFTER TURBULENCE
UNIFORM SPHERE
SURFACE DENSITY (GM./CM.^{2})
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10^5
10^4
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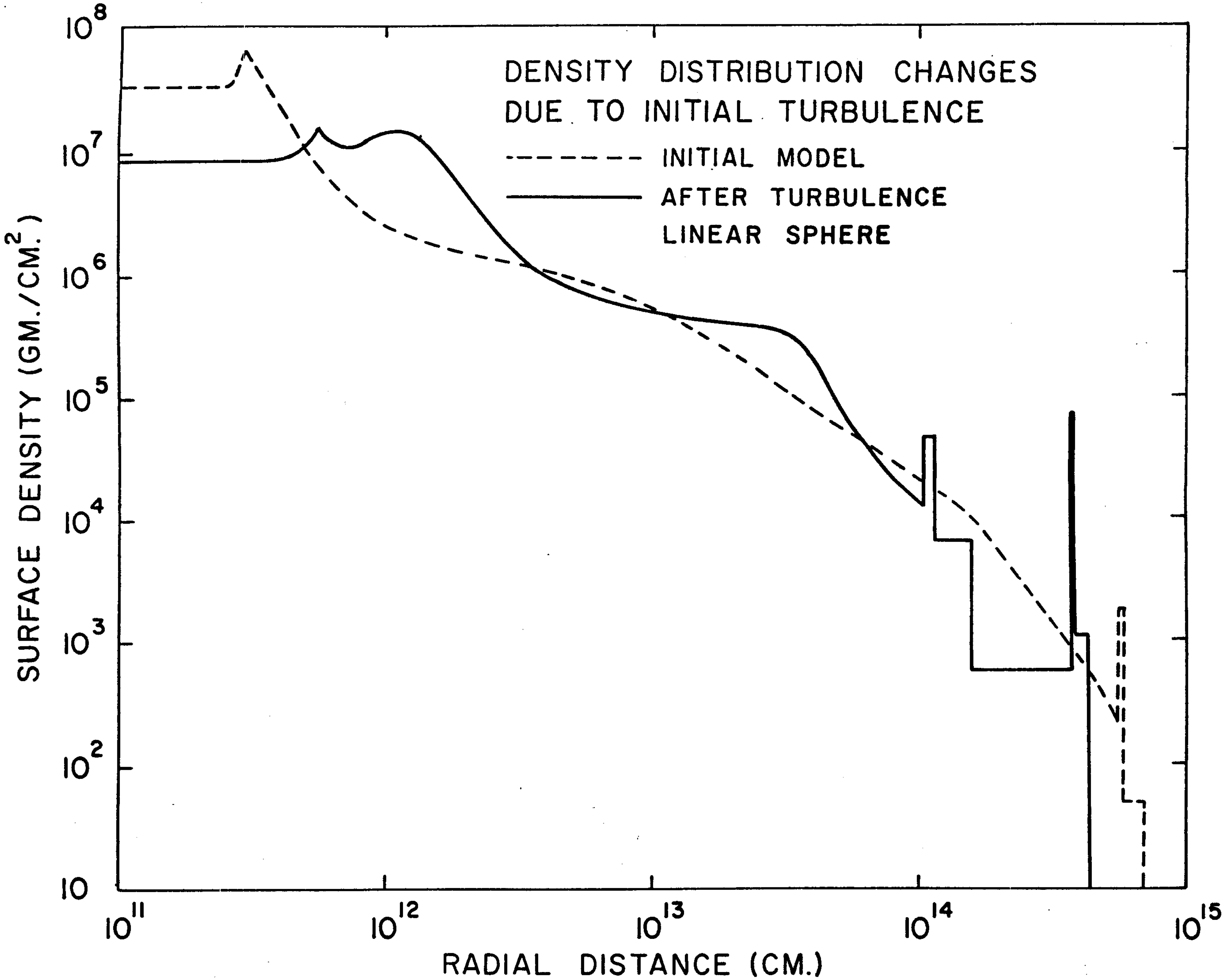
10^{15}
RADIAL DISTANCE (CM.)

Figure 2


DENSITY DISTRIBUTION CHANGES
DUE TO INITIAL TURBULENCE
INITIAL MODEL
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SURFACE DENSITY (GM./CM.^{2})
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RADIAL DISTANCE (CM.)

Figure 3