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SEQUENCE OF EVENTS IN THE EARLY PHASE OF THE SOLAR SYSTEM

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The purpose of this note is to construct a sequence of events in the early phase of the solar system by bringing together several recent theories in different fields of learning. First we show that these theories are mutually salutary. Thus, when we put them together, a reasonably clear picture of the formation of the planetary system emerges.

In a recent investigation by Fowler, Greenstein and Hoyle (1) (2), it has been assumed that there was strong magnetic activities on the surface of the primeval sun. The light elements, lithium, beryllium and boron were then produced according to them by spallation processes when high-energy particles (mainly protons), which had been accelerated by the electromagnetic force on the solar surface, bombarded the dense material in the solar nebula. Furthermore, they have concluded from observed fact that at the time of being bombarded the planetesimals in the solar nebula must be on the average of 12 meters in radius if their shape was spherical.

In the meantime Hayashi (3) (4) has shown that the pre-main sequence stars must be in a convective equilibrium. He and his associates have calculated evolutionary tracks in the H-R diagram for these stars of several masses including the solar mass. Their results differ from the previous model based on the radiative equilibrium (5) (6) by the high luminosities in the early phase of the evolution before the main sequence.

In a paper by Faulkner, Griffiths and Hoyle (7), a question as regards the consistency between Fowler's and Hayashi's theory has been raised, because in Fowler's theory, it is required that the temperature in the solar nebula must be low -- a requirement that appears to contradict the high luminosity

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obtained by Hayashi. However, in a recent article (8) we have argued that the temperature in the solar nebula can be low even when the luminosity of the primeval sun is high if the solar nebula is opaque enough in the directions in the plane of disk (9) (10). Since the charged particles which follow the magnetic lines do not necessarily travel in the plane of disk, the high density in the disk does not prevent charged particles to bombard the planetesimals in the disk.

More recently, Poveda (11) has presented a theory of flare stars. The success of his theory for explaining the location of these stars in the H-R diagram indicates the sound reasoning of his arguments. Now, if we follow the same reasoning as he does in his investigation of flare stars, we can immediately conclude that not only Hayashi's theory presents no difficulty to Fowler's theory, but the two are mutually conducive. In order to see this point, we have to describe briefly Poveda's theory.

The flare stars show very rapid and non-periodic changes in brightness (12). They are always dwarfs stars of late spectral types. It has long been suggested that the flare stars obtain their variations of luminosity in a similar manner as the solar flares do (13) (14). Since it is generally known that solar flares are a result of magnetic activities which are in turn caused by convective motion and differential rotation (15), Poveda argues that flares must be very active when stars are undergoing evolution where convection dominates. From the calculated results of Hayashi and his associates (4), Poveda is able to plot a curve in the H-R diagram on which convection stops to be a dominant factor. Thus the flare stars should all lie on that side of the curve where convection dominates and none on the other side. Indeed, that is just what has been observed.

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Then we have Schatzman's theory (16) of braking axial rotation of stars due to magnetic activities. Schatzman also invokes convective motion in the early phase of stars as the cause for magnetic activities and thereby explaines why axial rotation of the main-sequence stars stops at about F5 (17). In the case of the solar system, it is very difficult to understand the present distribution of angular momentum with its high concentration in major planets as representing the original state. Schatzman's theory provides an effective mechanism for braking the rotation of the primeval sun.

Thus, we have seen three theories (Fowler's, Poveda's and Schatzman's) which predict results in agreement with observed facts and at the same time all consistently require intensive magnetic activities in the primeval sun and one theory (Hayashi's) which satisfactorily explains the loci of new stars in the H-R diagram and, at the same time, provides the clue why there should be intense magnetic activities. All these four theories not only predict observed phenomena but also have strong theoretical base. Hence, the appearance of magnetic activities in the primeval sun may be regarded as an established fact.

It follows that we should inquire whether there are indeed magnetic activities in T Tauri stars and flare stars that are now evolving toward the main sequence. It appears that no such stars are on the list of magnetic stars discovered by Babcock (18). However, it should be noted that the magnetic field of a star has a good chance to be discovered only when it is systematic like that of a dipole field. When the magnetic activities in stars are chaotic as are envisaged by the previous theories, the lines of force are oriented at random. Hence, they are difficult to be discovered by polarization measurements.

Hayashi and his associates (4) have given the time at which the primeval sun stopped to be completely convective to be less than 10^6 years from the time of its initial condensation and the time at which the "hydrogen burning" began to be about 25 x 10^6 years. If we follow Poveda that the solar surface activities of the primeval sun became reduced to the present level when the evolutionary track based on the convective model meets that of the radiative model, the time of intensive magnetic activities proposed by Fowler and others would be confined to the first 8 x 10^6 years of the formation of the system. This is the time that has generally been accepted as the gravitationally contracting time of the sun (1). If the intensive magnetic activities occurred only when the sun was completedly convective, the formation of planetesimals of an average radius of 12 meters must have taken place in the first 10^6 years after the sun attended hydrostatic equilibrium. It is conceivable that the magnetic activities were more intense at the very early stage when the luminosity was high and convection complete than at later stages. If so, we may indeed expect that the formation of the planetesimals occurred in the first few 10^6 years.

Another supporting fact for the shorter time scale for the formation of planetesimals comes from a recent study by Hunger (19), who claims that contrary to the previous understanding (20) (21), T Tauri stars do not rotate rapidly because he has found many sharp stellar lines in three of these stars. He attributes the broad features previously believed to be due to axial rotation now to the blending of lines. It follows from his conclusion that axial rotation has already been reduced by magnetic braking before the evolving star becomes a T Tauri star.

We can now reconstruct the sequence of events in the early phase of the solar system from the previous and other theories. The early phase of evolution of the sun (or for that matter, any star) has often been divided into two stages: (1) the condensing or collapsing stage characterized by hydrodynamic inflow of matter and (2) the stellar stage characterized by hydrostatic equilibrium. According to recent studies (22) (23), the first stage is catastrophic if we neglect the effect of angular momentum and magnetic field. Gaustad (23) gives a time scale of 5×10^5 years for complete free-fall from interstellar densities to stellar conditions. The presence of a net angular momentum in the cloud prolongs somewhat the time of collapse. But from a consideration of the average angular momentum of the entire solar system observed at present we find that the effect of angular momentum on the time scale is small. Hence, we may take one half to one million years as the time that the sun underwent the first stage. The time scale of the second stage follows results given by Hayashi and his associates (4).

The early phase of evolution of the planetary system can be divided into two corresponding stages. The transition occurred when the evolution of the sun itself was at its second stage.

As masses were falling into the protosun, accumulation of mass by direct capture of non-volatile matter (24) (25) (26) to form small local condensations far away from the primeval sun took place in what may be regarded as the primeval solar nebula which was then distributed in a spherical symmetry with respect to the sun. We may regard it as the outermost layers of infalling material at low temperatures.

According to a recent investigation by Donn and Sears (27), the particles first formed in the solar nebula are expected to be filaments and thin platelets which they call whiskers. When the whiskers are collected together they form loosely compacted instead of solidly packed condensations. Thus, the condensations in the solar nebula would have a structure resembling the lint-balls under beds or balls made of tumbelweeds that roll in the wind over the prairie under the fall sky.

Regarding the mass of these local condensations we may take the clue from Fowler's planetesimals which may be estimated from their radii to be 10^{10} gm on the average. For various reasons, a density of 10^{-9} gm/cm^3 has often been assumed for the flattened solar nebula. With this density the rate of growth of condensations by direct accumulation of mass can be calculated (24) (25). It grows about 1 cm in radius in 1/3 to 30 years, independent of the size of the body itself (25). In the spherical distribution before flattening, the density must be less than 10^{-9} (say 10^{-11} to 10^{-13}) and the rate of growth would be correspondingly slower. However, it may be noted that the previous rate was obtained (25) by assuming that the accumulating body is solidly packed. For the porus body the rate of growth in radius is faster by a factor inversely proportional to the ratio of the over-all density to the mass density of the porus body. Thus, we estimate the time of formation of condensations of mass comparable to Fowler's planetesimals to be about 10^6 years. The formation took place when the solar nebula was spherical distributed. This time scale is consistent with the time scale of solar evolution. It also agrees with the fact that the orbits of comets now observed are radomly oriented, indicating that the local condensations took place when the solar nebula was still spherical.

When strong magnetic activities appeared in the sun in its second stage of evolution before reaching the main sequence, the transfer of angular momentum from the sun to the solar nebula induced inevitably the collapse of the solar nebula from a spherical distribution to a disk one. This marks the transition of the evolution of the solar nebula from the first to the second stage. Therefore, the transition from the first stage to the second stage for the sun and that for the solar nebula are not supposed to occur at the same time but differ by an interval which covers the time for developing strong magnetic fields in the sun from hydrodynamic motion and for transporting angular momentum outward.

The local condensations might be temporarily heated up and perhaps melt during the collapse, or a rapid accumulation of matter in the process might fill their porus matrix. In any case the local condensations must have lost their porus nature and became planetesimals that Fowler envisaged when they were settled down in the rotating disk to be bombarded by high-energy particles from the sun. The collapse of the solar nebula from a spherical to a disk distribution being about 100 years if the nebula extended not far beyond Pluto's orbit, we may regard that these planetesimals received all their dosage of bombardment when they were already in the rotating disk.

The solar nebula has a life time of 2×10^8 years (25). Therefore, the formation of planets from the planetesimals must have taken place in a time scale less than this value. By considering first direct capture and then gravitational accretion, Kuiper (25) has found that this time scale is only barely enough to form planets. However, we are inclined to suggest that the formation of planets from planetesimals may take a much shorter time than this. Our reasoning rests on the fact that the planetesimals are gravitationally unstable. One can easily visualize this instability by imagining a large number of planetesimals floating in space. A slight increase in density at one point (due to statistical fluctuations) will easily cause a rapid inflow of these bodies to that point, thereby producing a condensation of the planet size. If so, the time of formation is simply the free-falling time. Since the free falling started from a density of 10^{-9} which is more than 10^{10} times the interstellar density, the free-falling condensation of proto-planets would take only a few years.

Two points should be noted here however. First, this kind of gravitational instability is not what is known as Jeans instability which applies to a gaseous medium (28). Secondly, the present instability would be damped when gas and dust are present together with planetesimals. Therefore, it might take a longer time to form major planets. In any case, it is very likely that when the sun reached the main sequence stage (i.e., when energy dissipated is completely balanced by energy produced by thermonuclear reactions of converting hydrogen into helium), the solar system was practically in the same state as it is now found.

We now propose that because of the difficulty of transporting angular momentum to great distances, the collapse of the solar nebula into a disk occurred only in the solar neighborhood, perhaps not far beyond the orbit of Pluto. Local condensations within this limit must all have fallen into the disk. For even if they survived the initial collapse, their later crossings of the disk, which reduce their vertical velocity component, would force them to follow the general motion of gas and dust in the disk.

The local condensations contained in that part of the spherical distribution that did not undergo the collapse continued their accretion of matter by direct capture until the remnant of the solar nebula was completely dissipated. We have mentioned that at the time of formation of the disk, the local condensations had an average mass of about 10^{10} gm each. Further accretion made these condensations to reach the comet masses of 10^{15} - 10^{17} gm each. Since these condensations have not suffered catastrophic collapse and have remained far away from the sun all the time, they maintain the porus nature till today as comet nuclei (29).

It follows from the above considerations that comets must have been much more numerous in the early days of the solar system, because there was a large volume (corresponding to the uncollapsed portion of the solar nebula) which contained these cometary nuclei. Gradually, however, the cometary nuclei were perturbed by planets either to the vicinity of the sun and were then disintegrated or to large distances from the sun and were thereby survived. The latter forms the reservoir of comets at large distances from the sun from which the present observable comets come as a result of stellar perturbation. Except by putting the original formation beyond the orbit of Jupiter, the present picture follows what has been proposed by Oort (30).

We have seen that events in the early phase of the solar system formed a natural sequence one necessarily leading to the next. Consequently, we have now good reasons to expect that the existence of planetary systems around main-sequence stars, especially of spectral type later than F5 where axial rotation stops, must be common in the universe as has been heuristically suggested before (31).

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