ORIGIN OF THE SOLAR NEBULA

Prof. Fred L. Whipple kindly agreed to be the chairman for all three panels, and introduced the next speaker, Prof. F. Hoyle, who spoke on 'The Solar Nebula'.

Hoyle: I would like to begin this contribution by considering the deductions we can make by comparing the gross chemical compositions of the planets with the composition of the Sun. For this purpose I have divided the planets into the three groups shown in

TABLE I

Augmented Masses of the Planets

	Jupiter Saturn	Uranus Neptune	Terrestrial planets
Major constituents	H, He	C N O	Mg Si Fe
Solar mass fractions (%)	100	1.5	0.15
Present planetary masses	100	10	1
Multiplier	1	67	670
Augmented masses (10^{-5} $M_{\odot}$)	100	670	670

The second line gives the mass fractions in the Sun of the major constituents of the planetary groups, while the fourth line gives the factors by which the present masses must be multiplied to give the amounts of solar material needed to yield the appropriate amounts of main planetary constituents. The interesting points emerge that Jupiter and Saturn require the least amount of solar material, and that Uranus and Neptune on the one hand and the terrestrial planets on the other require approximately equal amounts. The total requirement is for $\approx 10^{-2}$ $M_{\odot}$ This is less by a factor ≈ 10 than the amount postulated in many theories of the origin of the planetary system. However the amount we have now calculated can readily be seen to be consistent with angular momentum requirements.

The main angular momentum contributed by the augmented masses comes from Uranus and Neptune and is $\approx 5.10^{51}$ gm/cm^2 sec (a mass $\approx 1.5 \times 10^{31}$ gm moving at ≈ 6 km sec^{-1} at $\approx 5.10^{14}$ cm from the Sun). Suppose that this amount of angular momentum was present in the primitive Sun. At what stage of its contraction did the Sun become rotationally unstable?

One would like to convert the radius of gyration k into an actual radius, but this requires us to estimate the degree to which the primitive Sun was centrally condensed. Models suggest $k^2 \approx 0.1$ R^2, where R is the actual radius at any moment. The angular velocity ω is therefore given by

$$MR^2\omega \approx 5 \times 10^{52}.$$

De Jager (ed.), Highlights of Astronomy, 195–203.

Rotational instability occurs when the kinetic energy per unit mass at the equator of the rotating Sun became of the same order as the gravitational potential energy,

$$R^2\omega^2 \approx GM/R.$$

Eliminating ω and inserting the mass of the Sun and of the gravitational constant G gives

$$R \approx 4 \times 10^{12} \text{ cm}.$$

That is to say, the primitive Sun became rotationally unstable when its radius was of the order of the radius of the orbit of the innermost planet, Mercury.

Next a few words about the nature of the rotational instability. If this were of a purely hydrodynamic nature the Sun would remain rapidly rotating. A hydromagnetic coupling, of the nature first proposed by Alfvén, is required if the Sun is to be left slowly rotating. Also the mass accumulating in an outer disk would very likely be much too large in the purely hydrodynamic case. Evolution into a binary star system would be expected in this case, rather than evolution into a star plus planets.

Once a planetary disk became separated from the primitive Sun, at $R \approx 4 \times 10^{12}$ cm, the inner and outer regions very likely became magnetically coupled, It is of interest to calculate the magnetic intensity needed to transfer most of the angular momentum from the primitive Sun to the outer disk. Provided the lines of force of the magnetic field bridge any gap that develops between the primitive Sun and the outer disk and provided the lines of force are rotationally twisted so that they emerge from the Sun at something like 45° to the radial direction, the transverse force exerted by the field $\approx H^2/4\pi$ per unit area. Multiplying by $\approx R^2$ for the total effective area, by $\approx R$ to obtain the couple, and by T the time scale of the process, we require

$$(4\pi)^{-1} H^2 R^3 T \approx 5 \times 10^{51}.$$

Putting $R = 4 \times 10^{12}$ cm, and using $T \approx 10^{11}$ sec for the duration of the convective contraction phase at this value of R, gives $H \approx 100$ G. This is a not unreasonable field.

Let us suppose that as a consequence of angular momentum passing from the primitive Sun to the planetary material, the latter was made to move further and further outwards. Then it became easier and easier for the light gases, hydrogen in particular, to escape from the planetary material back to interstellar space. Let us see if we can calculate the stage at which this occurred. For this we note that the extra velocity required to promote escape, over and above the orbital velocity, is $(\sqrt{2}-1)\,(G\,M/r)^{1/2}$ at distance r, provided the extra velocity is directed in the sense of the orbital motion. It is reasonable to suppose that escape will occur when the velocity of sound in the gas is of the order of this extra velocity,

$$(\gamma\kappa T)^{1/2} \approx (\sqrt{2}-1)\left(\frac{GM}{r}\right)^{1/2},$$

where γ is the ratio of specific heats, κ is the gas constant, T the temperature, and the gas is taken to have atomic weight $\approx$ unity. Throughout the condensation of the primitive Sun the surface temperature was ≈ 3500 K, so that

$$T \approx 3500\,(R/r)^{1/2},$$

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where R is the solar radius, as before. These two equations give $r \approx 5 \times 10^{14}$ cm, using $R = 4 \times 10^{12}$ cm, $\gamma = \frac{5}{3}$. It is satisfactory that this estimate is close to the radius of the orbit of Neptune.

This argument strongly suggests that the light gases do not escape directly from the region of the terrestrial planets to interstellar space, but that an intervening stage occurs with the gases being pushed away from the Sun due to the acquisition of angular momentum.

The terrestrial planets formed close to the Sun because the materials of which these planets are composed condensed as solids and liquids from the gaseous phase. Thermochemical calculations show that Mg, O condensed at ≈ 1600 K, Fe at ≈ 1500 K, and SiO_2 at ≈ 1400 K. These temperatures occurred when $r/R \approx (\frac{7}{3})^2$, i.e. $r \approx 2 \times 10^{14}$ cm for $R \approx 4 \times 10^{12}$ cm, giving a value of r close to the radius of the orbit of the Earth. The Fe condenses directly as a metal not as an oxide. Very likely it was sticky so one might plausibly suppose that Fe condensed and became aggregated into bodies of appreciable size, and that this was the first stage in the formation of the terrestrial planets. The iron cores of Earth Venus are likely to have formed first.

It is of interest that the above picture fits better to the current theory of stellar condensation than it does to the older theories. The higher surface temperature, ≈ 3500 K, throughout contraction gives better agreement with the chemical and dynamical requirements.

Recently, as a result of the work of Wasserburg and his colleagues at the California Institute of Technology, it has become possible to say a little about conditions immediately preceding the formation of the Sun. Studies of fission – produced xenon from Pu^{244}, together with fission track densities, in certain meteorites have shown that of the order of 10% of nuclei built by fast neutron addition must have been synthesised within $\approx 10^8$ yr of the formation of the solar system. It is not yet known whether the process of synthesis was local, for example in a nearby supernova, or was widespread throughout the Galaxy. A major event in the galaxy, generating r-process elements, and inducing a widespread phase of star formation is an interesting possibility.

Whipple: In Professor Hoyle's model, I am concerned by the relatively high temperature. It makes Mercury and Venus difficult to build, but particularly prevents comet formation in the region of Uranus and Neptune. I believe the evidence is strong that Uranus and Neptune were formed by ice cometismals – as the terrestrials planets were formed by earthy planetismals.

Schatzman: One of the problems concerning the origin of the planets concerns the formation of the primitive nebula which is impossible to describe without knowing how the contraction of the rotating proto sun has taken place.

This can be approached in two steps, the first one consists in finding the internal structure of a non-rotating proto-Sun; the second step consists in applying the results of the first step to the rotating proto-Sun. The reason for considering these two steps is the following: A non-rotating proto-star of about one solar mass, between a radius of 10000 $R_\odot$ and 100 $R_\odot$ (that is to say from about the distance of Pluto to the distance of Mercury) is known as being dynamically unstable, due to the dissociation of

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molecular hydrogen and then to ionization of hydrogen. The possibility of stabilization by supersonic turbulence, generated by convective transport of energy, has been suggested by Schatzman. In principle, the effective gamma, Γ_{eff}, can be brought above $\frac{4}{3}$ by a sufficiently high turbulence:

$$3\Gamma_{\text{eff}} - 4 = \frac{(3\gamma - 4)\, P_g + P_t}{P_g + P_t}$$

However, Cameron (1969) has criticized this model on the basis that supersonic turbulence, due to its high dissipation rate, cannot be maintained. To meet Cameron's criticism, I have derived, from the equations given by Ledouc and Walraven (1958), new phenomenological equations for the balance of the turbulent energy and for the balance of the normal energy. Next a series of physical assumption are made: the turbulence is supposed to have larger velocities, the contraction is supposed to be radial and to follow a law of homology. Finally, the star is supposed to have a structure very close to the polytrope 3. It is then checked whether the strong postulated turbulence can actually be fed by the contraction and the heat flow generated by it.

It turns out that the hypotheses are not self-consistent, which means that the star can never build a turbulence strong enough to make the star dynamically stable. The consequence is that, from having a radius comparable with the orbit of Pluto to one comparable with the orbit of Mercury, the proto-Sun will evolve in free fall. In other words, from the orbit of Pluto to the orbit of Mercury, the contraction will take place in only a few hundred years.

When estimating then the turbulent diffusion coefficient, it is then found that the rate of transport of any physical quantity is too small for it to take place during the time of free fall. Considering now a rotating proto Sun, the transport of angular momentum cannot take place inside the proto-Sun during its contraction throughout the whole region where the planets are to be found. It is concluded that the formation of the primitive nebula takes place without exchange of angular momentum.

References

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Hoyle: Schatzman has drawn attention to the rapid collapse of the primitive Sun, a few centuries was the time scale he mentioned. I agree that the time scale was so short that conditions were essentially free-fall at a radius comparable to the orbits of Uranus and Neptune. But free-fall stopped before the radius fell to the value I considered in my contribution, $\approx 4 \times 10^{12}$ cm. The free-fall time from this radius is only about two weeks, not a few centuries. I also agree that the free-fall situation at large radius is a good reason why the process of planetary formation had to wait until radii of $\approx 4 \times 10^{12}$ cm were reached.

Herbig: It seems to me that if we really believe that star formation today operates under the same rules as it did 5×10^9 yr ago, then we have to conclude that among the very young stars in the solar neighborhood there may be phenomena taking place today, before our eyes, that bear directly upon the origin of our planetary system.

In other words, this subject may not be the sole province of chemists, physicists, and meteoriticists, but may lean in an important way upon the input provided by stellar and interstellar astronomy.

Just a few examples: (1) We have heard about the time in the history of the early Sun when the solar nebula was being radially dissipated. We see what appears to be just this process in operation in VY Canis Majoris today; (2) The depletion of Ca, Ti, and possibly Al in the interstellar gas, while Na and K are normal (with respect to H), is a well-known phenomenon. Precisely this pattern of depletion and normalcy is to be expected as a result of freezing of refractory compounds (such as complex silicates) out of the gas of a 'solar nebula', and the subsequent return of this depleted gas to the interstellar medium. (3) The phenomenon of the decay of surface activity as a star like the sun evolves down its Hayashi track to the main sequence and afterwards, is exhibited clearly by the phenomenon (studied most recently by O. C. Wilson) in which the strength of the chromospheric H and K lines serves as an index of the stars age. The same process is seen in the decay of the solar wind, which in the Sun's T Tauri days must have blown at the rate of 10^{-8} yr^{-1}, while after 5×10^9 yr it has decayed to $10^{-13} \odot$ yr^{-1}. (4) There is a theoretical point which seemed very important a decade ago, but which now seems to have been disposed of by direct observation: namely, that star formation is a multiple process resulting from the fragmentation of a massive object. There is excellent evidence that Nature herself does not feel bound by the limitation. Stars certainly form in twos and threes, and possibly one at a time, the explanation being the very low temperatures and high densities of dense H I clouds as revealed by modern radio-frequency observations.

I mention all of them to demonstrate that speculations on the origin of the Sun and the planetary system have clear interfaces with direct observation. There is, of course, some observational information that does not fit at all well, such as the remarkably high luminosities for T Tauri stars that result when their infrared excesses are added on.

There was hope a few years ago that studies of the lithium abundance in solar-type stars of all ages would provide new insight. I rather feel that this subject has not lived up to that initial promise. Possibly, studies of very cool objects such as some of the OH/H_2O microwave sources, and the Becklin-Neugebaur object in the Orion Nebula will lead to instructive results, but it is too early to be certain.

Gold: I want to discuss the processes that must have taken place to set up the present planets and satellites from the fine particles that first condense out of the solar nebula. The first question is how the condensation and accumulation processes would lead to bodies on orbits that are safe against collision. Clearly the first bodies that accumulate from fine particles have no reason for forming only on lanes so far separated from each other that they are forever safe from mutual collisions. On the contrary one must suppose that initially many bodies start to form and each grows until it is shattered by a collision. This process cannot go on forever since dynamical energy is lost into heat, and not replaced in dynamical form. In fact the process must become subject to a type of 'natural selection' whereby the system gradually evolves towards a collision-free one. One may expect that in such a system it will be approximately true that at any one time only very few collisions can be expected in an interval equal to the previous existence of the system. After five billion years we thus find the system in a configuration where collisions are rare on a time-scale of five billion years. It is interesting to note that this allows satellites around planets, and those exist, while it would not allow many more planetary bodies on lanes in-between those of the existing planets.

The accumulation processes will be helped by gas-drag in the early phase when a lot of gas is still present. We understand that in the presence of a non-conservative force a planetary-type system will tend to fall into commensurable motions, meaning that any one particle will tend to have the secular evolution of its orbits arrested when its period has a low number commensurability with the period of one of the perturbing forces. Accumulation processes will be favoured in lanes that satisfy such a condition of commensurability with planetary bodies then existing. This has important effects, both for making accumulation processes much faster than they would otherwise be, and for leaving the final system with systematic motions near to the commensurabilities that assisted in the formation. Bode's law and many features of satellite systems may find their explanation in these effects.

Cameron: The picture outlined by Professor Hoyle is a good example of the deductions which one may very well make by arguing backwards in time from the present state of the solar system, being conservative with assumptions about the angular momentum of the system and the minimum amount of mass required in the primitive solar nebula. My own approach to the problem has been rather different. I have examined the conditions which we now see in the interstellar medium to determine how star formation is likely to take place, and how star formation processes can be related to the origin of the solar system. The results which I have obtained give an extremely different picture of the primordial solar nebula than that which has just been presented by Professor Hoyle.

The time allotted to me does not allow me to present a full scientific justification for the results which I have obtained following this approach. I have time only to present some of the conclusions obtained from this approach.

The collapse of an interstellar cloud is probably induced by pressure fluctuations in the interstellar medium which can occur when a new O or B star turns on, or if there is a supernova explosion. The collapsing interstellar cloud breaks into fragments, and it is necessary to follow the history of one of these fragments. I do not believe that magnetic fields play a major dynamical role during this process, and hence the resulting fragment of the interstellar cloud collapses to form a disk of gas, axially condensed toward the center. However, this disk does not have a central body in hydrostatic equilibrium, since its dimensions are much too large for that.

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At the present time I am constructing numerical models for such a disk, which I assume to represent the primordial solar nebula. The models are based upon the assumption that there is centrifugal equilibrium in the radial direction and hydrostatic equilibrium in the vertical direction. The techniques for treating the centrifugal equilibrium of the gaseous disk are adapted from those which have been used in the study of galactic structure. The vertical hydrostatic equilibrium of the disk is treated using techniques derived from the construction of stellar models. The most important question concerning the vertical hydrostatic equilibrium is the determination of the temperature gradient, and hence the determination of whether thermally-driven convection is present in the disk.

The dissipation of such a gaseous disk occurs basically by an outward transport of angular momentum. This will be accompanied by an inward transport of mass throughout the majority of the nebula, but with an outward transport of mass near the outer edge of the disk. There is differential rotation in the disk, with the angular velocity decreasing rapidly with increasing radius, so that the dissipation process requires some sort of friction to occur between adjacent layers of the disk. The most effective type of friction arises from turbulent viscosity, and the turbulence in turn depends upon the presence of convection in the disk.

Some of the models which I have constructed contain thermally-driven convection from the center out to a radius of several astronomical units. The detailed evolutionary calculations of the disk structure have not yet been carried out. However, one can utilize the estimates of dissipation times for a turbulent disk which were made many years ago by von Weizsäcker and ter Haar, who estimated that the dissipation time of such a disk could be expected to lie in the range 100 to 1000 yr. At first glance, this is a startingly small time. Chemical condensations which occur in such a nebula will be carried into the forming Sun as the mass dissipates unless rather large bodies can form in a time comparable to this dissipation time.

I believe that planetary formation can occur very much faster than has been estimated for the collision of small particles in a vacuum, if a large amount of gas is present. The presence of convection together with radioactivity in the disk should suffice to build up relatively strong electric fields in the gas, and such electric fields also assist in the accumulation of small particles into bigger ones. I do not think it at all out of the question that planets like the Earth could form in a few centuries.

A necessary consequence of the rapid formation of the planet is the presence of an extremely high internal temperature, of the order of 10^4 K, and the proper study of planets in such an early high temperature phase has not yet been carried out.

There is really no problem in getting rid of the remaining gas in the solar nebula after the Sun has formed. The T Tauri phase of mass loss from the young star involves stellar winds of the order of 10^6 or 10^7 times the present solar wind. This very large rate of mass loss should not only terminate the lifetime of the solar nebula, but it is also ample to produce other interesting cosmogonical effects, such as the removal of primitive atmospheres from the terrestrial planets.

Hoyle: If the original planetary material has a mass large compared to 10^{-2} M

we have somehow to explain how a dissipative process managed to remove most of the material and yet contrived to leave a little. One feels that if the dissipation had been only marginally more effective all the planetary material would have been lost. The origin of the planets appears to be a matter of chance.

Of course one can argue that only in systems where planetary material survived could life in our form arise. So in this sense chance is removed. But then we would have to recognise that our situation is unlikely to be typical. The problems of planetary origin would be rendered more difficult, since it is more difficult to infer exceptional cases with precision than it is to understand a typical case.

Safronov: In the hypothesis by F. Hoyle the initial mass of the protoplanetary cloud is assumed to be about 10^{-2} of the solar mass while in the hypothesis of A. Cameron it is about the mass of the Sun. However both these values meet serious objections. The study of the rate of growth of the outer planets has shown that Uranus and Neptune could grow up to their present sizes in a few billions of years only if the density of the feeding material was almost an order higher than that calculated from their present masses. The giant planets at the final stage of their growth ejected solid bodies from the solar system by gravitational perturbations. We have found that the ejected mass of the solid material should be about 6 times that fallen on to planets. According to these considerations we have assumed the value 0.06 M_0 as a reasonable value for the initial mass of the protoplanetary cloud. The value of one solar mass assumed by A. Cameron seems to be too great. It is difficult to find the mechanism that could secure the ejection of the whole of this mass from the solar system.

Cameron: Dr Safronov has stated that it is impossible to accumulate the planets on a time scale of less than 10^7 yr. This assertion can only apply to the processes of accumulation which were considered by Dr Safronov, and which he did not state. I wish to point out that in the presence of a massive turbulent solar nebula, a wide variety of efficient processes of accumulation may be present.

One of these has to do with the fact that there will be a pressure gradient in the radial direction in the solar nebula, which will give a partial hydrostatic support to the gas, but which will not affect the solid bodies significantly. Hence the gas will rotate at a slightly slower rate than the solid bodies, leading to friction between the solid bodies and the gas which will lead to a progressive inward spiralling of the solid bodies.

Turbulence itself will lead to collisions between the solid bodies. However, probably the greatest effect of the turbulence is that it will separate the charges produced by the radioactivity in the nebula, leading to the buildup of electric fields. One may expect an approach toward equipartition of energy in which the electric field energy density would approach the energy density of the turbulence. However, this cannot be achieved because the gas would break down with lightning discharges long before that condition was reached. This indicates that the primitive solar nebula was undoubtedly a most complicated place. Small solid particles will be accelerated by electric fields when they carry charges, which will tend to make them run into one another much more rapidly, and lightning discharges may help to fuse them together.

When the accumulating bodies have reached a larger scale of size, then there will be important inertial effects associated with the interaction between the turbulent gas and the bodies. Bodies will overshoot the motions of the gas which tend to carry them along. Larger bodies will overshoot to a larger extent than the smaller ones, thereby causing them to run into many smaller bodies which are following different trajectories.

All of these processes, and probably others, must be taken into account in developing a theory of the accumulation of the planets. I personally do not see why accumulation times of much less than 10^7 yr should not be achieved.

Regarding the temperature of the planets, I wish to point out an inescapable consequence of Professor Gold's remarks that the planets may have been accumulated through the coming together of a few major pieces. If this has indeed happened, then the resulting gravitational potential energy release will of necessity produce interior temperatures in a planet like the earth of the order 10^4 K. This is something that would happen quite independently of the rate of accumulation of the major chunks out of which the planets were produced.