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THE ROLE OF PROTOPLANETS IN THE FORMATION OF THE SOLAR SYSTEM

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A likely origin of the asteroids (and possibly, of the comets?) is the natural outcome of the following scenario that we propose for the formation of the planets. Protoplanets of similar mass and solar composition will segregate in three different ways: For those far enough from the sun (like Uranus and Neptune), the segregation of icy grains releases enough energy to drive the remaining gases to infinity. For all other planets, the segregation of refractory material only does not release enough energy to disrupt the protoplanet ; however, while spiraling inwards in a resisting medium, the terrestrial protoplanets cross their Roche limit and lose their gaseous outer layers. Asteroids (or comets) could therefore originate from the disruption of protoplanets before the settling of their refractory (or icy) grains is completed.

If we look at a table of masses and general composition of the planets (Table I) then a remarkable fact appears, namely the mass divided by the cosmic abundance of their composition is remarkably constant at a value of a few hundred Earth masses. In other words, there could have existed a family of similar parent objects with a mass of the order of 2 x 10^{30} g and solar (or cosmic) composition from which the planets formed. Recent calculations on the structure of Jupiter and Saturn both need a rock and ice content of the order of 15 $M_{\oplus}$. (See Stevens 1977, for a review of this topic).

TABLE I

PLANETARY TYPE	MASS $M_{\oplus}$	COMPOSITION	COSMIC ABUNDANCE %
TERRESTRIAL	1	Iron Silicates	0.3
OUTER	15	C, N, O Compounds	2.0
MAJOR	300	Cosmic	100

We therefore suggest that the original solar nebula fragmented into such protoplanets. One possible mechanism for causing this fragmentation is turbulence as was originally suggested by McCrea (1960) and now also by Cameron (1977). Though there are a number of interesting problems associated with this

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stage of the process, it is not appropriate to discuss them here (see Williams 1975, for example for a review). Instead we discuss how the existing planets could emerge from such protoplanets.

Since the major planets have about the same mass and composition as protoplanets, the process envisaged here is simply one of contraction. Donnison and Williams (1974) have shown that such a protoplanet, contracting as a star, would reach Jupiter's present radius in the time available and that its luminosity would match that of the present day Jupiter.

Since the other planets have a different composition from the original protoplanets, some segregation process must have occurred within them. Segregation while all the constituents are in a gaseous state is clearly impossible to achieve and so the obvious suggestion is that the segregation occurs between the gas and materials that condense out of it. Any such condensates will cease to be supported by gas pressure and will settle towards the center of the protoplanet. This aspect has been considered in some detail (McCrea and Williams 1965, Williams and Crampin 1971, Williams and Handbury 1974) and the conclusion appears to be that while normal interstellar grains (radii ~ 10^{-5} cm) settle very slowly, larger grains or grains that grow, either by coagulation or condensation, have no difficulty in settling in an acceptably short period of time. We should expect this process of settling, which implies the formation of a core, to take place in all protoplanets. Consequently, such cores should exist within the major planets.

Of course, core formation releases gravitational energy and such an energy release could disrupt the protoplanet. Williams and Crampin (1971) considered this point and concluded that the segregation of refractory materials (including iron compounds) would not release enough energy to materially affect the protoplanets. This is of course as it should be for we do not need Jupiter to be disrupted. However, if the segregating grains were to be composed of both refractory material and ices (water, methane, ammonia, carbon dioxide for example) then the mass of segregating material is considerably increased and Handbury and Williams (1975) have shown that sufficient energy is released to drive the remaining gases to infinity. In this way objects would be formed very similar to the outer planets. Of course we still have to offer a reason why the ices segregated only in the outer planets. Handbury and Williams (1975) suggested that this was simply because they were the outer planets and therefore where the heating effect of the Sun was less leading to lower temperatures. This is probably far too simple a view of the situation for the incident radiation on the surface of a protoplanet is but one of many factors which determine the internal temperature, while formation of grains depends on other factors as well as temperature. This does not mean the suggestion is false, only that it is unproved. However, I will make another suggestion for this in a short while.

Turning now to the terrestrial planets. Of course forming a core is not sufficient, the gaseous outer layers must also be removed and clearly the most obvious source of a mechanism for doing this is the Sun since these planets are indeed closest to the Sun. Handbury (1975) had suggested that the wind from the Sun during its T Tauri stage was responsible for this. However the suggestion which I now believe is most likely is that it is the tidal effect of the Sun which was responsible. Donnison and Williams (1975) have shown that dispersal by this mechanism can be vary rapid for an object closer to the Sun that the Roche limit and it is significant that the Roche limit (see Jeans 1928 for a definition) for protoplanets of the general type envisaged lies at about the position of the asteroidal belt.

Of course these protoplanets could not therefore have been originally closer to the Sun than the Roche limit otherwise they would have been disrupted before core formation could take place and so a mechanism must be found to bring protoplanets closer to the Sun. Donnison and Williams (1977) have shown that the general effect of a resisting outflowing medium is to do this, and

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that significant changes in the orbit can occur in a reasonable time. The significance of the effect is of course dependent on the mass to cross section ratio of the protoplanet. The following scenario therefore suggests itself. Protoplanets form out of a solar nebula, whether all at the same time or singly is irrelevant, in general outside the Roche limit. All the condensed material segregates to the center to form a core. If conditions were such that ice grains existed, then this process of core formation disrupts the gaseous envelope, leaving only an icy core. This now has a small cross section compared to its mass and so is not affected by any resisting medium. Consequently these do not spiral in very far and remain in the outer reaches of the system. Others, however, do spiral closer to the Sun, and some cross the Roche limit. This allows the tidal effect of the Sun to disrupt the outer gaseous layers, leaving behind a terrestrial like object.

The main area of weakness within the theory undoubtedly lies in the fact that no real attempt has been made to discuss the structure of protoplanets. No one has investigated even the general question of whether it is possible for refractory material to be in a non gaseous state, never mind the more specific question of whether ice grains could exist in some protoplanets. These are questions to which it should be possible to obtain answers by using techniques similar to those already employed in investigations of a more conventional solar nebula. Until this is done some people may regard protoplanets as nothing but wild speculation. Be that as it may, I will now end with even wilder speculation concerning the origin of the asteroids.

There are three main processes envisaged above, settling of a core, inward spiralling of the orbit through the Roche limit and removal by tidal effects of the gas. What happens if a protoplanet crosses the Roche limit *before* settling is completed? Clearly it is disrupted and all that would remain would be whatever lumps of material that had already formed, in orbit in the general area of the Roche limit, that is the Asteroidal Belt. I would therefore contend that investigations of the asteroids can give very vital clues to the cosmogonists for they are remnants of a protoplanet (or indeed a number of protoplanets) that became disrupted in the process of forming planets. It is tempting to offer a similar explanation for the comets, but until the structure of protoplanets are better understood, it is impossible to say whether a small degree of settling of ice grains and snowballs could lead to the dispersal of some protoplanets.

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