SIMULTANEOUS GROWTH AND ORBITAL EVOLUTION OF TERRESTRIAL AND ASTEROIDAL EMBRYOS; G.W. Wetherill, Dept. of Terrestrial Magnetism, Carnegie Institution of Washington, 20015.

Most previous discussions of the origin of the asteroid belt and the growth of $10^{26}$ to $10^{27}\text{g}$ terrestrial planet embryos into final planets have assumed that in at least one of several conceivable ways, prior formation of Jupiter prevented the formation of runaway embryos in the asteroidal region (1,2) and limited the growth of Mars (3). Under these circumstances, in which embryos interior to Jupiter formed only in the terrestrial planet region, Monte Carlo simulations of the growth of these embryos usually result in the formation of 3 to 5 terrestrial planets, two or three of which are similar in mass and position to Earth and Venus. The growth of these planets is characterized by giant impacts of the magnitude hypothesized to be responsible for the formation of the moon (4,5) and the loss of Mercury's silicate mantle (6).

An alternative model of asteroidal origin has recently been presented, in which the formation of Jupiter and the other giant planets is delayed until after the growth of $10^{26}$ to $10^{27}\text{g}$ embryos in the asteroidal region (7). The present work is a major extension of that study to include a total of about 450 simulations of simultaneous evolution of growth and orbital elements in the terrestrial planet and asteroidal regions. For any particular combination of assumptions and adjustable parameters, about 15 calculations were made, in order not to be misled by the intrinsically stochastic nature of the processes involved. The large number of calculations carried out permitted exploration of a wide range of variant models, involving different assumptions regarding the strength and position of secular and commensurability resonances, variation of surface density with heliocentric distance, and modelling of fragmentation processes. The final outcome of these calculations was found to be insensitive to these variations. This has the advantage that similarities between the results and the observed solar system should not be considered to be simply the consequence of special choices of parameters. On the other hand, this finding also has the consequence that discrepancies between these results and observations probably represent more deep-seated problems that could prove difficult to understand.

It is found that a large fraction (95 to 100\%) of the mass of the primordial asteroid belt is removed gravitationally by the same mechanisms responsible for removal of asteroidal meteorites and the Earth-approaching asteroids at present: perturbations by outer-planet resonances and close planetary encounters into Jupiter crossing, as well as by collision with planets. The primordial effects are more efficient than those at present, because perturbation into resonances caused by mutual gravitational perturbations between embryos are stronger than those resulting from the present dominant process of fragmentation. Collisional fragmentation does play a primordial
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role, however. In its absence it is usually found that one \(10^{26} - 10^{27}\)g embryo remains in the asteroid belt. Mutual perturbations also provide a quantitative explanation of the present asteroidal relative velocities of \(-5\) km/sec.

In the earlier calculations, in which asteroidal embryos were not included, the initial swarm parameters were chosen to match the present mass, angular momentum, and energy of the terrestrial planets. In the present calculations, the values of these quantities are initially very different than at present. It is found that they spontaneously evolve to match quite well those observed. Because the initial configurations are much less constrained than those assumed earlier, it should be expected that a greater range of final terrestrial planet configurations will result. This is the case, but our terrestrial planet system belongs to the same general "class" of such observed systems found by the simulations. The principal difference is that a planet 2 to 3 times as massive as Mars is often found at \(-1.6\) AU.

When considered along with the earlier simulations, a by-product of these calculations is the finding that an approximately Earth-mass planet is formed near \(1\) AU regardless of whether or not asteroidal embryos are formed. Such an object is also formed even when it is assumed that no gas-giant planets are ever formed (7). In the latter case, additional \(>10^{27}\)g bodies are formed in the asteroid belt as well. This ease with which "Earths" are formed about stars of solar mass is attributable to this region being sufficiently deep within the Sun's potential well to limit gravitational ejection of bodies, and to the weakness of giant planet resonances interior to \(2\) AU.

It is concluded that the initial conditions considered here lead to a viable alternative to those in which Jupiter suppresses embryo formation in the asteroid belt, particularly in the light of the present lack of a quantitative model for accomplishing such suppression. This new model provides a wide range of possibilities for the interpretation of the meteoritic record and asteroidal observations. Ultimate choices between alternatives will rest upon their theoretical consistency and accord with observational data.

REFERENCES