WHY ISN'T MARS AS BIG AS EARTH? G.W. Wetherill, DTM, Carnegie Institution of Washington, Washington, D.C. 20015 U.S.A.

A prominent feature of the distribution of solid material in the Solar System is the absence of bodies more massive than one percent of Mars' mass between Mars and Jupiter. The small mass of Mars is often viewed as a precursor to this mass deficiency in the asteroid belt. It is conceivable that the mass deficiency is a relic of the radial mass distribution in the primordial dust-gas solar nebula, even though present models of star and planet formation provide no support for this hypothesis.

A more conventional view is that the surface mass density of the solar nebula decreased more or less monotonically with heliocentric distance, except for a jump in surface density at the "snow line" (5 A.U.?) beyond which H_2O is condensed. A model of this kind requires removal of solid material between 1 and 5 A.U. at some later time, most likely during the growth of the terrestrial planets and the asteroids. At present, there is no quantitatively adequate theory that explains satisfactorily just how this mass removal occurred. On the other hand, the number of physical mechanisms whereby mass could have been transported out of this region is limited, and quite likely they are all known, at least in a general way. Usually it is proposed that "Jupiter did it" (e.g. 1) in one way or another. Despite unresolved difficulties, this may be the case for the asteroid belt (2), but becomes increasingly difficult to understand for smaller heliocentric distances, i.e. between 1 and ~ 2.3 A.U. This situation is aggravated by the probable runaway growth of $> 10^{26}$g terrestrial planetary embryos on time scales of 10^4–10^5 years, requiring formation of Jupiter on a time scale that is likely to be prohibitively short (3,4).

This investigation is directed toward quantifying some possible ways of "compressing" a swarm of 10^{25}–10^{27}g planetary embryos originally extending out to 2.35 A.U. into the narrow band between ~ 0.7 and 1.1 A.U. required to match the angular momentum and mass of the observed system of terrestrial planets. It is an extension of work published earlier for a more restricted class of models (5). A process of this sort is contrary to the usual situation whereby an accretion disk that dissipates energy, but conserves angular momentum, spreads in heliocentric distance. The required compression can be achieved, however, if angular momentum is not conserved, but instead is transferred to the gaseous component of the solar nebula, which contains almost all of its mass. Two potentially important mechanisms for accomplishing this have been proposed:

1. Outward transport of angular momentum via spiral density waves in the gaseous nebula (6,7).

2. Transfer of angular momentum from the embryos to the nebular gas by gravitationally enhanced gas drag (8). Although the Reynolds number assumed by Takeda were much lower than those expected for a non-turbulent nebula, they may be appropriate to a nebula with a moderate degree of turbulence.

Expressions for the decrease in semi-major axis, eccentricity, and inclination caused by these mechanisms have been incorporated into the Monte Carlo technique used by the author to study the final stages of terrestrial planet formation (9). The narrow distribution of mass vs. heliocentric radius used in earlier calculations has been replaced with mass distributions extending out to 2.35 A.U. Various assumptions regarding the loss of nebular gas from this region on a time scale of 10^6–10^7 years have been studied.

In all cases, a growing central minimum in the radial gas distribution is required to prevent excessive loss of material into the sun when presently fashionable assumptions are made regarding turbulent viscosity in the solar nebula.

It is found that, acting alone, the Takeda gas drag mechanism is capable of providing, on the average, about 40% of the required angular momentum and energy loss. The spiral density wave alternative, using parameters given by Ward is considerably more effective. A more complete treatment of this phenomenon (Ward, private communication) suggests that these parameters are likely to be too large. Reduction of these values by a factor of two leads to angular momentum and energy losses about 65% of those required. Acting together, the two mechanisms may provide a fully adequate transfer mechanism, particularly if augmented by "late stage cleaning out" of high angular momentum residual bodies by Jovian commensurability resonances after the later formation of Jupiter at $\sim 10^7$ years.

This conclusion should not be interpreted as strong advocacy of the hypothesis that transfer of angular momentum to nebular gas was indeed a major factor in inhibiting the growth of full-size terrestrial planets in the region of Mars and the inner asteroid belt, if only for the reason that understanding of the fundamental physics of these mechanisms is still at an early stage. Rather, this work shows, in a moderately quantitative way, that attributing the limited size of Mars to effects caused by a very early-formed Jupiter may not be the only, nor even the best, way of explaining this observational fact.

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