THE FORMATION AND HABITABILITY OF EXTRA-SOLAR PLANETARY SYSTEMS; G.W. Wetherill, DTM, Carnegie Institution of Washington, Washington, DC 20015

A model that successfully predicts a number of the general features of the terrestrial planet and asteroidal regions of our Solar System (1,2) has been extended to include variations in stellar mass and pre-planetary disk surface densities. The biological habitability of the resulting planetary configurations has also been investigated using the habitability criteria of Kasting et al. (3). A principal result is that for stellar masses between 0.5 and 1.5 $M_\odot$, the resulting planetary configurations are insensitive to differences in stellar mass (Fig. 1). For initial surface density distributions similar to those of our Solar System, large terrestrial planets tend to concentrate near 1 AU, regardless of stellar mass. This region is habitable only for ~ 1 $M_\odot$ stars. A smaller, but significant, number of planets occur at habitable distances for all the stellar masses studied, however.

It is assumed that terrestrial planetary systems originate by accumulation of centrifugally supported residual material derived from circumstellar disks similar to those observed about pre-main sequence stars. At present, there is no reason to believe that the total mass or the mass distribution in these disks is approximately the same as that in the disk from which our Solar Systems was formed. This investigation addresses the question of the sensitivity of the resulting planetary configurations to variations in disk parameters and to differences in stellar mass.

About 500 new simulations of planet formation have been made using essentially the same program used to investigate the formation of the terrestrial planet and asteroidal regions of our Solar System (1,2). For each set of parameters, over 20 simulations have been made in order to distinguish between the stochastic variations that result from the chaotic nature of the accumulation process, and differences attributable to the choice of parameters.

The following results were found:

(i) As mentioned earlier, for initial solid matter surface density distributions appropriate to our Solar System, planets larger than ~ 1/2 $M_\oplus$, tend to concentrate near 1 AU, regardless of stellar mass (Fig. 1). Large planets of small stars will therefore be too cold, those of large stars will be too hot, and solar mass stars will be "just right" (known as the Goldilocks problem (4)).

(ii) For the same variation of surface density with distance from the central star, this concentration of planets near 1 AU is also insensitive to surface density. The mass of the planets is approximately proportional to the surface density, however. If the surface density of solid material is too low, perhaps less than ~ 1 g/cm^2, the planets may be too small to retain an atmosphere.

(iii) The calculations described above assumed the existence of a "Jupiter" and a "Saturn" at distances similar to those of our Solar System. Moving these outer planets closer by a factor of 2/3 begins to deplete the abundance of large planets near 1 AU without increasing it elsewhere. The population of the 1 $M_\odot$ habitable zone near 1 AU is thereby decreased. Moving these giant planets further out by a factor of 2 permits the formation of Earth-size planets in the asteroidal region and greatly enhances the population of the habitable zone for 1.5 $M_\odot$ stars. Complete absence of the giant planets permits the formation of very large (up to ~ 5 $M_\oplus$) bodies in both the asteroidal and terrestrial planet regions. The habitability of these planets may be reduced if "failed" ~ 10 $M_\oplus$ "Jupiters" permit an excessive bombardment by outer Solar System bodies (5).

(iv) Abundant formation of possibly habitable large planets in association with small (~ 0.5 $M_\odot$) stars requires variation of solid surface density with distance from the star that is quite different from that of our Solar System. Tidal locking of the rotation of such near-by planets may also expose their biota to severe climatic stresses (3,6).

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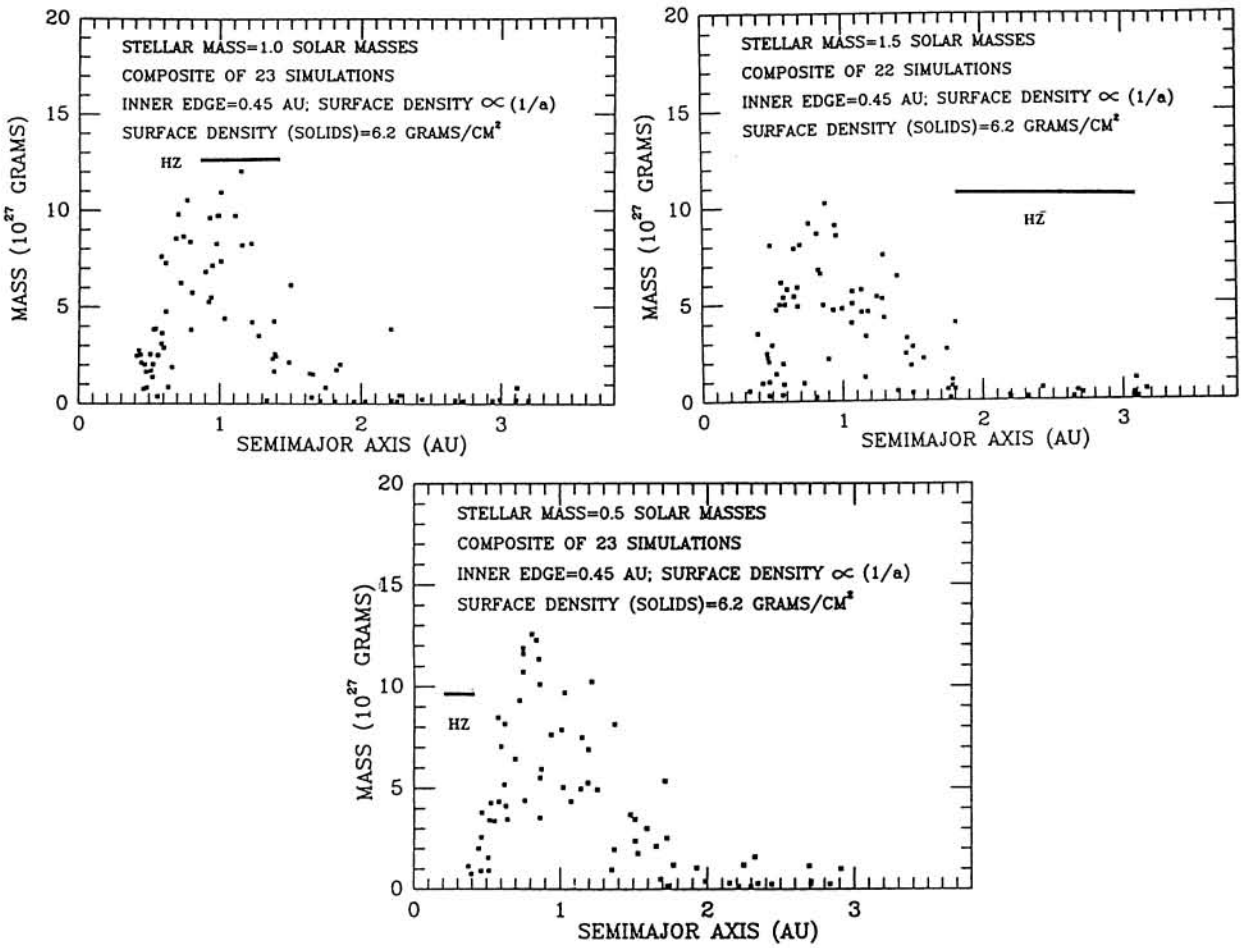

Fig. 1. Final positions of all planets with mass > 10^{26}g (~ lunar size) formed in about 20 simulations for three values of stellar mass. In all cases, large planets are concentrated near 1 AU. "HZ" represents the limits of habitable zones (0 to 1000 m.y.) for each stellar mass (3).

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