THE FORMATION OF LIFE-SUSTAINING PLANETS IN EXTRASOLAR SYSTEMS.

J. E. Chambers, *NASA Ames Research Center, Moffett Field CA 94035, USA, and SETI Institute, 2035 Landings Drive, Mountain View CA 94043, USA, (john@mycenae.arc.nasa.gov).*

Introduction: One of the characteristics that makes Earth a suitable environment for the origin of life is the presence of significant amounts of water and other volatile materials. It is thought that Earth formed by the accretion of a large number of small, rocky planetesimals which formed in the inner part of the Sun's protoplanetary nebula (Wetherill 1990). However, protoplanetary nebula models indicate that planetesimals forming at 1 AU from the Sun would have been very dry, containing little or no volatile material (Cassen 2001). This suggests that Earth obtained most of its volatiles by accreting planetesimals that formed elsewhere in the nebula. These planetesimals would have been driven onto Earth-crossing orbits by gravitational perturbations from the giant planets, principally Jupiter and Saturn.

The most likely sources of these planetesimals are (i) the outer Solar System (i.e. comets), and (ii) the main asteroid belt. In these regions, the nebula was substantially cooler than at 1 AU, allowing some volatile material to condense and become incorporated into planetesimals. The high collision probability with Earth of asteroids, and the Earth-like D/H ratio seen in meteorites, suggests that asteroids were the dominant source of Earth's volatiles (Morbidelli et al. 2000), although comets must have contributed too. Earth could have accreted large amounts of asteroidal material if runaway accretion took place in the asteroid belt, as suggested by Wetherill (1992). This is because large planetary embryos had a greater chance of colliding with Earth than smaller planetesimals from the same source region (Morbidelli et al. 2000).

Here, I will assume that this scenario is correct, and examine whether something similar could have taken place in extrasolar planetary systems. These systems possess different giant-planet configurations than the Solar System, so the number of volatile-rich planetesimals perturbed onto orbits where they can be accreted by Earth-like planets will also differ. Currently, it is unclear whether any of the observed extrasolar systems has the right configuration to permit the formation and survival of an Earth-like planet. Instead, I consider artificially generated systems, produced by varying the masses m and orbital elements of Jupiter and Saturn. Many of the processes involved in the origin of Earth's volatiles are poorly constrained at present. For example, an unknown fraction of the water delivered to Earth was lost during impacts or by reacting with iron. Here, I will assume that these processes are comparable on all Earth-like planets, and concentrate solely on differences that result from the giant-planet configuration of each system.

Simulations: Planetary accretion is a highly stochastic process, so it is desirable to run an ensemble of several simulations for each combination of model parameters. In addition, Earth's volatile budget is fairly small (e.g. the water present in Earth's oceans and mantle represents 0.0004 of the planet's mass), so each simulation must contain a large number of initial bodies in order for a few to collide with each terrestrial planet. State-of-the-art planetary accretion simulations typically use N-body integrations (e.g. Chambers 2001), but these are too computationally expensive for the current problem. Instead, I use a modified version of the Öpik-Arnold scheme (c.f. Wetherill 1967), used extensively in early simulations of planetary accretion (e.g. Wetherill 1986). The original algorithm has been modified to include an approximate treatment of resonances and secular perturbations associated with the giant planets, since these play an important role in perturbing bodies from the asteroid belt into the terrestrial-planet region.

Giant planets	t=0	3 Myr	10 Myr
Jupiter & Saturn	0.9	0.7	0.5
Jup., (4 AU), Sat. (9.5 AU)	0.6	0.6	0.6
Jup. (7 AU), Sat. (12 AU)	0.4	0.4	0.8
Jup., Sat. (m x3)	0.5	0.5	0.5
Jup. & Sat. (both m/3)	0.8	0.9	0.9
Jup. & Sat. (both i x10)	0.7	0.6	0.7
Jup. & Sat. (both e x2)	0.1	0.5	0.4
Jup. & Sat. (both m/3, e x4)	0.0	0.1	0.1

Table 1: Number of habitable planets per system for different giant-planet configurations, as a function of the time t at which the giant planets form. Note that m x3 implies that the mass of the giant planet was increased by a factor of 3 etc.

For each giant-planet configuration, the first step is to make a "map" of the giant-planet perturbations using a set of test-particle integrations. These integrations last for 50 million years (Myr) and include particles with orbital semi-major axes in the range 0.5–8 AU. The integrations yield the approximate lifetime of an object in each system as a function of a and the orbital eccentricity e. In the modified Öpik-Arnold scheme, objects in unstable regions have a chance of being lost after each time step, with a probability determined from the test-particle integrations. Secular perturbations from the giant planets are treated in an approximate way by imposing slow sinusoidal oscillations on e and i for each object. The period and amplitude of these oscillations depend on the body's semi-major axis, and are determined using the dominant peaks in the power spectra of e and i from the test-particle integrations.

Altogether, I have examined 8 giant-planet configurations, including Jupiter and Saturn of the Solar System. For each system, I have made 30 planetary accretion simulations, grouped into batches of 10 according to the time at which the giant planets are introduced. In the 3 batches of simulations, the giant-planet perturbations are "switched on" after 0, 3 or 10 Myr respectively.

Giant planets	t=0	3 Myr	10 Myr
Jupiter & Saturn	.0007	.0013	.0060
Jup., (4 AU), Sat. (9.5 AU)	.0001	.0022	.0033
Jup. (7 AU), Sat. (12 AU)	.0055	.0092	.0109
Jup., Sat. (m x3)	.0003	.0003	.0017
Jup. & Sat. (both m/3)	.0048	.0042	.0078
Jup. & Sat. (both i x10)	.0003	.0006	.0021
Jup. & Sat. (both e x2)	.0002	.0003	.0005
Jup. & Sat. (both m/3, e x4)	.0001	.0002	.0005

Table 2: Volatile mass fraction for final planets interior to 2 AU (mass-weighted mean for all planets), as a function of the time t at which the giant planets form.

Giant planets	t=0	3 Myr	10 Myr
Jupiter & Saturn	0.7	0.6	0.5
Jup. (4 AU), Sat. (9.5 AU)	0.1	0.3	0.6
Jup. (7 AU), Sat. (12 AU)	0.4	0.4	0.8
Jup., Sat. (m x3)	0.1	0.0	0.3
Jup. & Sat. (both m/3)	0.8	0.9	0.9
Jup. & Sat. (both i x10)	0.3	0.3	0.2
Jup. & Sat. (both e x2)	0.1	0.1	0.3
Jup. & Sat. (both m/3, e x4)	0.0	0.1	0.1

Table 3: Number of "life-sustaining" planets per system for different giant-planet configurations, as a function of the time t at which the giant planets form.

Each simulation begins with about 10000 planetesimals, with masses in the range 0.0005–0.05 Earth masses. The initial masses are drawn randomly from a power law distribution with index -2.5, such that most of the mass is in the smallest bodies. Objects are distributed in a disk moving on roughly circular, coplanar orbits, with a between 0.4 and 8 AU. Each object is assigned a volatile content according to its distance from the star: objects inside 2.5 AU contain no volatiles, those with a of 2.5–5 AU contain 10% volatiles by mass (similar to carbonaceous chondrites), while bodies outside 5 AU contain 50% volatiles. Collisions produce a single new body which represents the largest collision fragment. The mass of this fragment is calculated using the collision-scaling law of Melosh and Ryan (1997), with the critical energy modified by a factor of 2 to account for a range of impact angles. Smaller fragments are assumed to be lost from the system as "dust".

Results: The simulations involving Jupiter and Saturn produced systems of inner planets that broadly resemble the terrestrial planets of the Solar System. The mean number of final planets inside 2 AU is 4.1, 3.3 and 3.0 for simulations in which the giant planets are added after 0, 3 and 10 Myr respectively. The mean mass of largest planet is 0.77, 1.00 and 1.13 Earth masses respectively, while the mass-weighted mean semi-major axis is 0.91, 0.93 and 0.95 AU respectively compared to 0.90 AU for the terrestrial planets. However, in common with previous accretion simulations, the final planets generally have more eccentric orbits than Earth and Venus.

Table 1 shows the mean number of "habitable" planets generated in each system. Here, a habitable planet is defined as one with a mass of at least 0.3 Earth masses, located in the habitable zone of a Sun-like star: 0.95–1.37 AU (Kasting et al. 1993). Most simulations involving Jupiter and Saturn produced at least one habitable planet. In general, changing the characteristics of the giant planets reduced the number of habitable planets per system, except when the masses of the giant planets were reduced. The number of habitable planets appears to be independent of the time at which the giant planets form.

Table 2 shows the volatile mass-fraction of the material contained in the final planets within 2 AU of the star. For comparison, the Earth currently has a volatile fraction of at least 0.0004 (i.e. the mass of water contained in the oceans and mantle). It is clear that the amount of volatiles delivered to the inner planets increases when the giant planets are located further from the star, and vice versa. High-mass giant planets, and ones with large eccentricities and inclinations lead to volatile-poor inner planets in most cases. There is also a strong correlation between the formation time of the giants and the amount of volatiles delivered to the inner planets.

Table 3 shows the number of "life-sustaining" planets per system. These are defined as planets in the habitable zone with a volatile fraction of at least 0.0004. Note that this definition is more conservative than it appears since it does not account for volatiles subsequently lost in impacts or by reacting with iron etc. Most giant-planet configurations result in fewer life-sustaining planets than Jupiter and Saturn, with the exception of systems containing low-mass giants on low eccentricity orbits. There is a weak trend towards increasing number of life-sustaining planets with increasing time of giant-planet formation.

In summary, these results suggest that the presence of habitable and life-sustaining planets in extrasolar systems will strongly depend on the masses and orbits of the giant planets in these systems.

References

Cassen, P. (2001) *Meteoritics Plan. Sci.,* **36** 671–700. Chambers, J.E. (2001) *Icarus,* **152,** 205–224. Kasting, J.F., Whitmire, D.P. and Reynolds, R.T. (1993) *Icarus,* **101,** 108–128. Melosh, H.J. and Ryan, E.V. (1997) *Icarus,* **129,** 562–564. Morbidelli, A. et al. (2000) *Meteoritics Plan. Sci.,* **35,** 1309–1320. Wetherill, G.W. (1967) *JGR,* **72,** 2429–2444. Wetherill, G.W. (1986) in *Origin of the Moon*, Lunar and Planetary Institute, Houston, TX, p519–550. Wetherill, G.W. (1990) *Ann. Rev. Earth Plan. Sci.,* **18,** 205–256. Wetherill, G.W. (1992) *Icarus,* **100,** 307–325.