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Research Article

Occurrence of Earth-Like Bodies in Planetary Systems

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Present theories of terrestrial planet formation predict the rapid "runaway formation" of planetary embryos. The sizes of the embryos increase with heliocentric distance. These embryos then merge to form planets. In earlier Monte Carlo simulations of the merger of these embryos it was assumed that embryos did not form in the asteroid belt, but this assumption may not be valid. Simulations in which runaways were allowed to form in the asteroid belt show that, although the initial distributions of mass, energy, and angular momentum are different from those observed today, during the growth of the planets these distributions spontaneously evolve toward those observed, simply as a result of known solar system processes. Even when a large planet analogous to "Jupiter" does not form, an Earth-sized planet is almost always found near Earth's heliocentric distance. These results suggest that occurrence of Earth-like planets may be a common feature of planetary systems.

According to currently fashionable theory, the growth of the solid planets of our solar system began by accumulation of the dust contained in a primordial circumstellar solar nebula to form a large number of small planetesimals (*1*). After the size of the planetesimals reached 1 to 10 km their further growth was controlled by collisional and gravitationally dominated interactions between one another. Recent studies of this stage of planetesimal growth have concluded that, in the region of the terrestrial planets, planetesimals grew in 10^4 to 10^5 years to form planetary embryos of the size of the moon to Mercury by a process of runaway accumulation (*2*). The final stage of solid planet formation then consisted of the collisional merger of the embryos to form the planets observed today. During this final stage of growth, the mutual gravitational perturbations of the growing planetesimals caused their relative velocities to increase to over 5 km s^{-1}. This increase caused their growth rates to decrease, and as a result the time scale for terrestrial planets to grow to nearly their present sizes was $\sim 10^8$ years.

Two-dimensional (*3*) and three-dimensional (*4*) simulations of the final stage of growth seem to explain a number of features of the observed terrestrial planets. In these earlier model simulations, in order to match the angular momentum and energy of the model to the observed planets, it was assumed that the planetesimals were initially confined within a narrow band, about 0.5 AU (astronomical units) in width, that was smaller in radial extent than the orbits of observed terrestrial planets. In the context of a more general model of solar system formation, this restriction of planetesimals to a narrow band seems artificial. On the other hand, a simple extension of the original distribution to include the region beyond about 1.1 AU led to disagreement with the observations that there are no bodies more massive than $\sim 10^{24}$ g in the asteroid belt and that the total asteroidal mass is small. It also failed to explain why Mars is smaller than Earth and Venus.

In order to proceed further, additional physical mechanisms are required. One such possible explanation of the observations is that rapid growth of Jupiter into a massive planet in $\sim 10^6$ years caused gravitational perturbations sufficiently strong to rapidly pump up the relative velocities of the planetesimals beyond the orbit of Earth to ~ 100 m s^{-1}. Such velocities could preclude the runaway growth of embryos in the part of the solar system between Earth and Jupiter and limit the growth of the asteroids to objects $\lesssim 10^{24}$ g in mass.

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After their relative velocities were further increased to the currently observed values averaging about 5 km s^{-1} (*5*) their mutual collisions would lead to their destruction and subsequent loss from the solar system by well-understood nongravitational forces. In one of several possible ways, it has usually been thought that Jupiter was also responsible for this additional increase in asteroidal velocity. Explanations of this kind require that Jupiter formed and prevented runaways on a time scale that was shorter than 10^5 to 10^6 years, the time found to be sufficient for runaway embryos with masses greater than 10^{27} g to form in the asteroid belt. It is quite possible that a satisfactory model in which Jupiter plays these roles will be developed, and will ultimately lead to an understanding of the evolution of the inner solar system. On the other hand, it is not clear that Jupiter could have grown so rapidly, even if its silicate-rich core consisted of a massive runaway embryo that formed on a time scale similar to the asteroidal embryos (*6*). This problem is particularly severe for the region between the orbit of Earth and the inner edge of the main asteroid belt at 2.17 AU because of the shorter time for runaway growth and the greater distance from Jupiter of this region. Recent calculations (7) indicate that time intervals of about 10^7 years may be required for Jupiter to accrete nebular gas and grow to its present great mass.

Asteroidal runaways. Because of these problems, I have explored an alternative possibility. It will be assumed that runaways indeed grew rapidly throughout both the asteroidal and terrestrial planet regions and that the runaway bodies reached their final sizes significantly earlier than the time at which Jupiter perturbations became important. This alternative has probably not received attention because the large ($\gtrsim 10^{27}$ g) runaway embryos expected to form in the outer part of the asteroid belt would be nearly invulnerable to mutual collisional destruction during the 4.5-billion-year age of the solar system, and this would seem to present serious problems in understanding the approximately thousandfold decrease in the mass of material in the asteroid belt since planetary formation began.

The calculations reported here address the possibility that large asteroidal runaway embryos can gravitationally perturb one another sufficiently to random walk their semimajor axes into one of the strong Jovian commensurability or secular resonances and that this may lead to a solution to the difficulties described. Chaotic acceleration of asteroid fragments in the vicinity of resonances has been demonstrated for the 3:1 commensurability (*8*), and is likely to be a general property of strong resonances. Commensurability resonances cause the strongly depleted Kirkwood gaps observed in the present asteroid belt and the ν_6 secular resonance determines the position of the inner edge of the belt. Acceleration by these resonances is responsible for much of the mass loss from the asteroid belt today. At present, however, because of the small size of the surviving asteroid population, gravitational perturbations between the asteroids are of negligible importance. For this reason, material is lost into the resonant regions only from bodies already near enough to the edge of a resonant region that their collision fragments, ejected at moderate velocities of ~100 m s^{-1}, can be injected into the resonant zone (*9*). In contrast, the gravitational perturbations of the much larger runaway primordial embryos should have been adequate to cause them to deflect one another into a resonant zone from any part of the asteroid belt. Because this self-clearing of runaway embryos permits removal of large bodies in the asteroid belt without requiring their fragmentation, it only becomes necessary for Jupiter to grow on a more leisurely ~10^7-year time scale, determined by the requirement that Jupiter be formed before the nebular gas was dispersed. It may also be possible that mutual perturbations between embryos and planetesimals provided the mechanism that accelerated the residual small nonrunaway asteroidal bodies with masses $\lesssim 10^{24}$ g to their present high velocity. This process would have caused the mutual fragmentation of these asteroid-size bodies that led to their present highly evolved size distribution and to the small total mass of the asteroid belt.

Monte Carlo simulations of planetary growth. The quantitative evolution of a model in which embryos formed in the asteroid belt was studied by Monte Carlo computer simulations of planet formation. The embryos were initially distributed all the way out to near the edge of the currently stable asteroidal belt, at a heliocentric distance about 3.3 AU, rather than being confined to the narrow band extending only from about 0.6 to 1.1 AU that was assumed in earlier simulations of planetary growth and orbital evolution (*4*).

The masses and semimajor axes of an assumed initial swarm are shown in Fig. 1. This swarm extends from 0.45 to 3.3 AU, and the total initial mass of the swarm was equal to 4.3 Earth masses. The masses and spacing of the initial embryos were primarily controlled by requiring that their initial orbits be spaced by 3.5 times their mutual "Hill sphere" radius (the distance from the body to its colinear Lagrangian points) as required to provide quasi-stability to nearly circular and coplanar concentric orbits (*6, 10*). As discussed in (*11*) this requirement leads to a relation among the mass (M) of the embryo, its semimajor axis (a), and the surface density (σ) of solid material:

$$M = 8 \cdot 2^{1/2} \cdot 3^{1/4}\pi^{3/2}a^3\sigma^{3/2}M_{\odot}^{-1/2} \quad (6)$$

where $M_{\odot}$ is the solar mass. The surface density of solid material was taken as 6.2 g cm^{-3} at 1 AU and to decrease with heliocentric distance as $1/a$. It is assumed that the time required for runaway formation varied linearly with the orbital period, that is, with the 3/2 power of the semimajor axis, and also linearly with the surface density of solids, and led to runaway growth times of 3.0×10^4 years at 0.7 AU and 1.4×10^6 years at 3.3 AU. To avoid artifacts that might be caused by such a nonphysical monotonic initial distribution, I multiplied each initial mass by a random factor between 0.75 and 1.25. The initial eccentricities were chosen such that the aphelion of one embryo overlapped the perihelion of its next more distant neighbor by 20 percent. Jupiter was assumed to be formed later, after 5 million years. After the formation of Jupiter, the

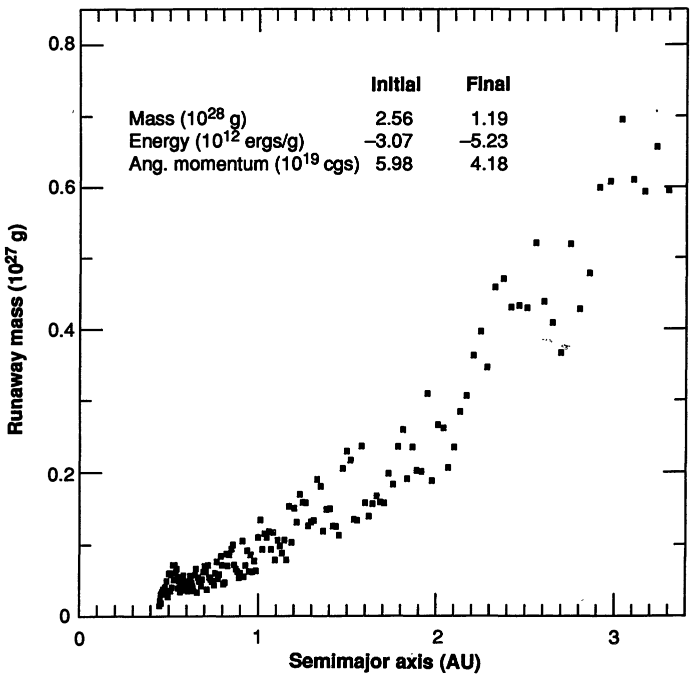

Fig. 1. Initial mass and distances of the runaway bodies in a swarm extending out to 3.3 AU. Ang momentum, angular momentum per gram (in centimeters squared per second).

4:1, 3:1, 5:2, 7:3, and 2:1 commensurabilities and the low inclination portion of the ν_6 secular resonances were assumed to exist at their present distances. The effect of Jupiter formation was taken to be ejection of all bodies with aphelion greater than 4.5 AU to solar system escape orbits on a short ($<10^6$ year) time scale, in accordance with the results of numerical integration of the evolution of bodies in orbits of that kind in the present solar system (*12*). I represented the accelerations associated with the resonances by resetting the eccentricity of bodies having semimajor axes within ±0.02 AU of the center of a resonance region to random values between 0.2 and 0.8, but not more than once every 2×10^5 (or in some cases 1×10^5) years. Because a libration condition protects bodies near the resonance from close encounters with Jupiter, ejection into an escape orbit was not permitted when the semimajor axes of the bodies were in the resonance region. Dropping of this assumption assuming that Jupiter formed at 10 million years, or assuming that initiation of the ν_6 effects were delayed to 10^7 or 2×10^7 years had no noticeable effect on the outcome of the calculations, however. An alternative resonance-acceleration algorithm in which the eccentricity underwent a random walk while in the resonance also led to no significant difference in the final outcome of the calculation. The spontaneous orbital evolution of the swarm was followed in time by use of the same Monte Carlo techniques described in (*4*).

Results of calculations. Contrary to what might be expected, it is found that this large change in the assumed initial distribution of embryos does not necessarily lead to formation of a planetary system that contains terrestrial planets in the asteroid belt. Instead, the self-clearing process described above often produces a system in which the asteroid belt is free of planet-size bodies. As in the present solar system, the self-clearing of the inner asteroid belt is assisted by perturbation and collisions with larger bodies in the terrestrial planet region. The clearing of the outer asteroid belt is primarily caused by resonant and mutual embryo perturbations. In either case, most of the loss of asteroidal material is ultimately the result of close encounters with Jupiter. In its final state, the region within ~2 AU of the sun contains only about four planetary bodies, of which usually only one is of approximately "Earth" size and one is of "Venus" size or slightly smaller. The remaining mass is found in a few smaller bodies, an outcome quite similar to the terrestrial planet configuration actually observed.

It was found (Fig. 2) that the specific energy and angular momentum of the swarm evolved from its low initial values to the vicinity of the present values of these quantities. This evolution was caused by increases of eccentricity in the resonant regions and preferential ejection from the system of the more distant bodies possessing higher angular momenta and higher (less negative) initial energies.

The positions of the final planets resulting from combining 27 of these simulations are shown in Fig. 3 (solid squares and open circles). The final radial distribution of planets is very different from the initial distribution of embryos. Because the results of 27 simulations have been combined, an estimate of the number of planets in a single episode of planet formation that will be formed in a given mass and semimajor axis range can be made by dividing by 27 the number of points in that range seen in Fig. 3. On the average, 4.2 simulated planets inside the inner edge of the present asteroid belt are produced. Usually one approximately Earth-size (6×10^{27} g) planet is found between 0.8 and 1.3 AU, and a second $\sim 4 \times 10^{27}$ g body is found at slightly larger or smaller semimajor axes. About two still smaller planets tend to form near the inner or outer edges of the final distribution. Analogs of Mercury almost always are collision fragments, as concluded earlier from studies of a narrowly confined initial swarm (*13*). In only about one-third of the simulations, a small (moon to Mars size) body is produced in the asteroid belt. Although no attempt has been made to explore the full many dimensional parameter space associated with models of this kind, a total of about 200 simulations have been carried out with embryos extending out as far as 3.8 AU and with alternative parameters or assumptions. These indicate that the general features of the final state bodies do not depend critically on the choice of the details of the model. For example, in some calculations (crosses in Fig. 3) the spacing of initial embryos was assumed to be 5 times the mutual Hill sphere radius rather than $2\sqrt{3}$ times this distance. As a result, the initial masses of the embryos were about twice as large.

Other than this pronounced redistribution of material, other characteristics of the growth of the terrestrial planets (for example, their general growth time scale and Mars-size giant impacts) are found to be similar to those found for the case where swarms were initially confined to a narrow band in the terrestrial planet region. The

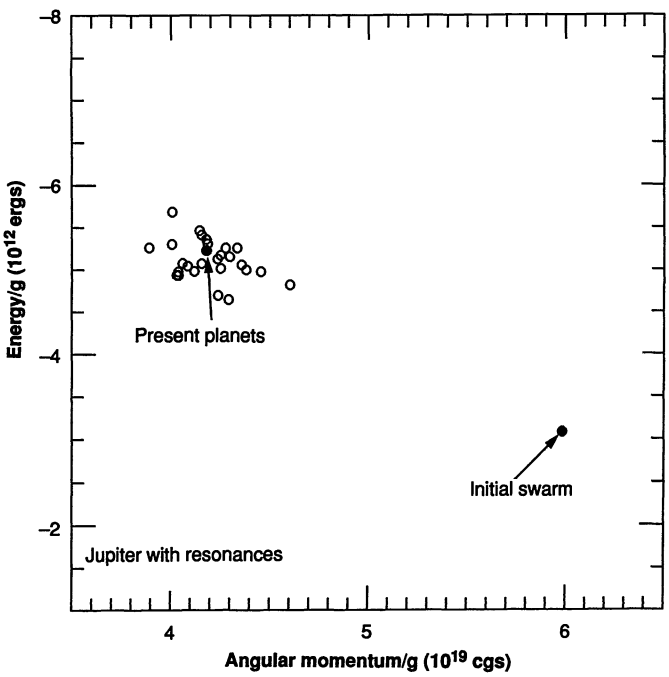

Fig. 2. Energy and angular momentum evolution when both Jupiter close encounters and resonant effects are included. The final state is close to that of the observed terrestrial planets.

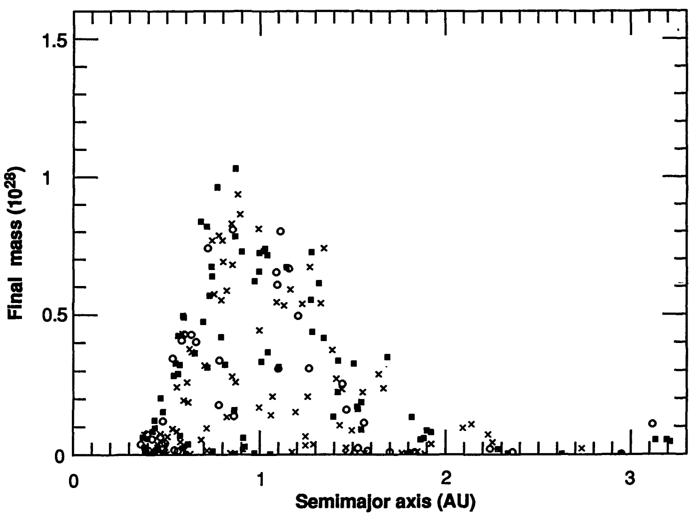

Fig. 3. Final distribution of planets for 47 combined simulations. Solid squares and open circles correspond to simulations plotted in Fig. 2. For the solid squares, the minimum time between resonance acceleration was assumed to be 2×10^5 years; for the open circles it was 1×10^5 years. The crosses represent simulations for which the initial spacing of embryos was larger (see text for discussion).

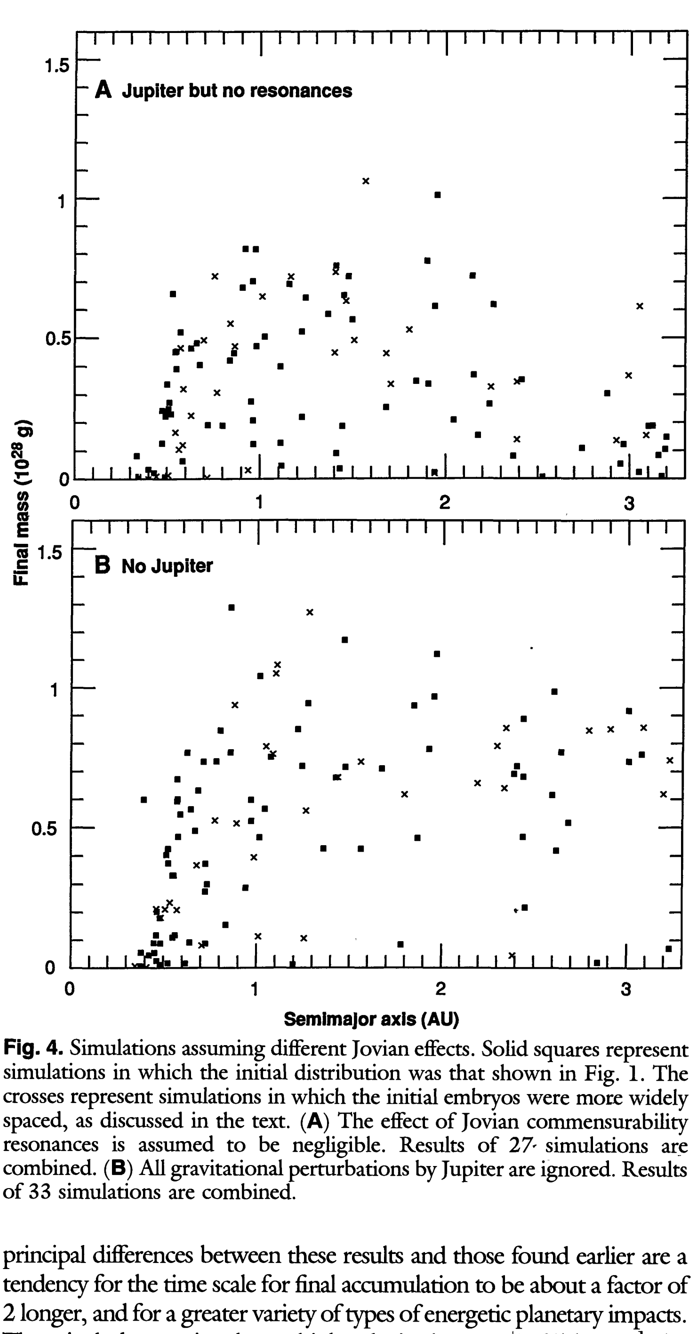

Fig. 4. Simulations assuming different Jovian effects. Solid squares represent simulations in which the initial distribution was that shown in Fig. 1. The crosses represent simulations in which the initial embryos were more widely spaced, as discussed in the text. (**A**) The effect of Jovian commensurability resonances is assumed to be negligible. Results of 27 simulations are combined. (**B**) All gravitational perturbations by Jupiter are ignored. Results of 33 simulations are combined.

principal differences between these results and those found earlier are a tendency for the time scale for final accumulation to be about a factor of 2 longer, and for a greater variety of types of energetic planetary impacts. These include occasional very high velocity impacts ($\sim$25 km s^{-1}) by small (moon to Mercury size) bodies, and impacts by bodies more than twice the mass of Mars for which the relative velocity (before mutual gravitational acceleration) is $\leq$2 km s^{-1}.

These results can be compared with those found when the effect of the Jovian resonances is assumed to be negligible (Fig. 4A) and when the presence of Jupiter is totally ignored (Fig. 4B). Even under these different circumstances, mutual perturbations between the runaway embryos cause significant loss of those bodies having higher values of energy and angular momentum. Earth-mass final planets are still found in the terrestrial planet region. The principal differences (compare Figs. 3 and 4) is that in the simulations without Jovian effects one or more large bodies are produced in the essentially empty present asteroid belt, and often smaller bodies are produced at heliocentric distances as great as 5 AU.

The position of the terrestrial planet accumulation zone is determined by its lying safely inside the region of strong commensurability resonances associated with a gas-giant planet like Jupiter, as well as being sufficiently deep within the gravitational well of the central star that the chance of the embryos being scattered by one another into solar system escape orbits is considerably reduced.

There are several ways in which the outcome of these calculations seems to differ from the observed distribution of the terrestrial planets. Although appropriately low values are sometimes found, the final eccentricities and inclination of the final large planets tend to be several times those observed. Also, planets in the range between 1×10^{27} and 4×10^{27} g are frequently found in the simulations, whereas none are observed in our solar system. It is not hard to propose possible qualitative explanations for these differences, but whether they actually represent minor or major difficulties will require more sophisticated investigations.

Possible implications for other planetary systems. These results suggest the speculation that for stars similar in mass to the sun, surrounded by centrifugally supported gas-dust disks with mass, energy, and angular momentum similar to that of our own primordial solar nebula, an Earth-like planet is likely to form near Earth's heliocentric position, even if for some reason a Jupiter-like planet does not form. In the presence of a Jupiter, the observed sequence of four terrestrial planets, a depleted asteroid belt, and then the first gas giant, may be a natural one. This regularity seems to occur despite the extremely chaotic and stochastic nature of the accumulation processes themselves. This latter factor, however, will probably preclude the frequent formation of terrestrial planetary systems with configurations precisely matching ours. Rather, one should expect to find a variety of similar terrestrial planet systems, with the second largest planet in some cases occurring farther from the central star than its larger neighbor, or in other cases containing planets the size of Mars or Mercury between the two large terrestrial planets, and occasionally in the asteroid belt.

This new model for terrestrial planet formation has many other implications that require further study. For example, preliminary studies in which small but indestructible "test bodies" are included in the swarm show that those few bodies that remain in the asteroid belt achieve a final velocity distribution similar to those of the observed asteroids. Also, the residual asteroidal material will contain fragments of both embryos and residual planetesimals that were not incorporated in the runaway; thus, a variety of thermal and chemical histories of asteroidal and meteoritical bodies should be expected.

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