Reports

Occurrence of Giant Impacts During the Growth of the Terrestrial Planets

Abstract. *Three-dimensional Monte Carlo simulations of the accumulation of the terrestrial planets in the absence of gas drag produced results that are in general agreement with the number and distribution of the present planets. The accumulation process appears to be characterized by impact of bodies as large as three times the mass of Mars at velocities of about 9 kilometers per second. These giant impacts on Earth may have supplied the material and angular momentum that formed the moon, should have heated Earth to the melting point, and may have been responsible for the differences in the content of inert gases of the atmospheres of Earth and Venus.*

If Earth and the other terrestrial planets formed by the accumulation of smaller bodies (planetesimals), then the size distribution of these planetesimals has an important bearing on the initial state of the planets, their atmospheres, and the way in which Earth's moon may have formed. Of particular interest is the question of the mass of the largest bodies that impacted the planets during their formation. Analytic theories of the growth of a single planet have been used to calculate the mass of the second largest body in the swarm of planetesimals from which the planet is assumed to have grown. On the basis of either the assumption that gas drag is not an important dynamic consideration (*1*, *2*) or that nebular gas was present (*3*), the formation of additional bodies in the mass range of approximately 10^{25} to 10^{27} g has been calculated.

Earlier studies based on the growth of only a single planet could not take into account the number, mass, and radial distribution of preplanetary bodies and the final planets, the size of the largest bodies that did not become independent planets (failed planets), or the orbital evolution of the planets while growing. In the present work the late stages of the simultaneous growth of several planets from planetesimals in a gas-free region of terrestrial planets are considered by use of three-dimensional numerical orbital calculations. This work is an extension of earlier calculations with a smaller number of initial bodies (*4*). The results have features in common with two-dimensional studies (*5*), but there are fundamental differences between two-dimensional modeling and the three-dimensional structure of the solar system.

Initial conditions for this final stage of planetary accumulation are those that may be expected from a prior stage of accumulation that started with planetesimals approximately 1 km in size (*6*). During this first stage, the number of bodies is sufficiently large and the spacing of their orbits is close enough that the bodies can be thought of as "particles in a box," as in the kinetic theory of gases. The swarm can be considered as consisting of concentric zones, within each of which moderately large bodies can accumulate independently of those of similar size growing in neighboring zones. For much of this stage, the eccentricities remain near the original low value of about 10^{-4} because most of the mass remains in small bodies (*7*). This stage ends as most of the mass shifts into larger bodies as the result of accumulation.

For an initial swarm corresponding to the present mass of the terrestrial planets and extending from 0.7 to 1.1 astronomi-

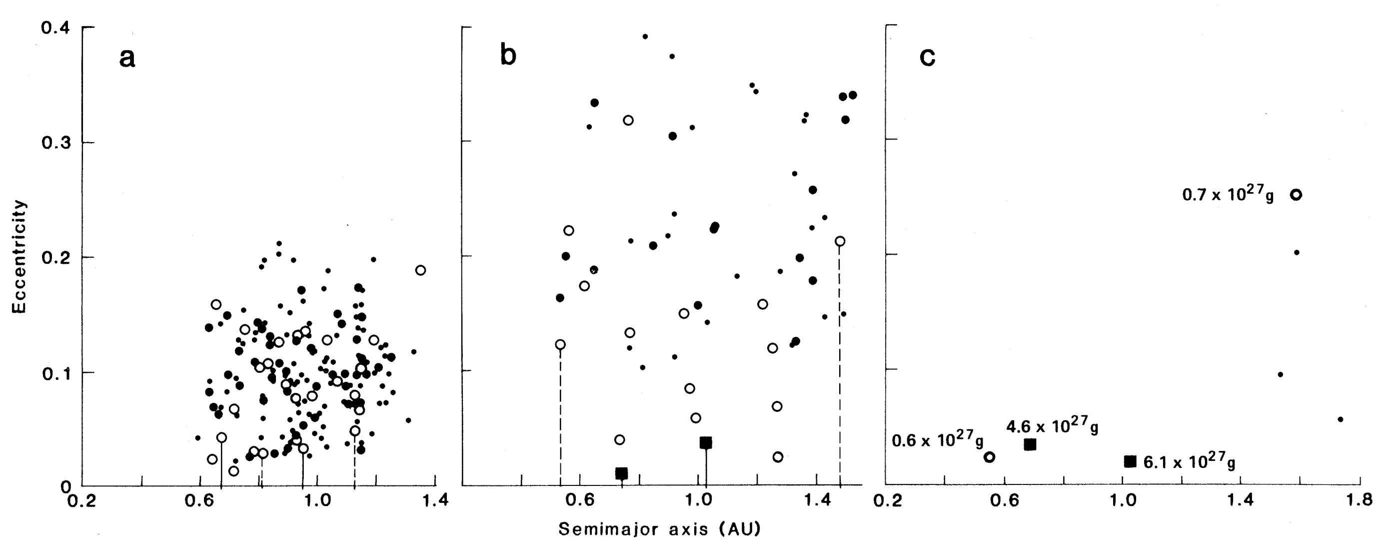

Fig. 1. Results of numerical simulation of accumulation of 500 bodies. (a) After 1.8 million years, 18 percent of the mass (~60 percent of the final radii) has accumulated in the final planets. The eccentricities have increased from low values of less than 0.05 to about 0.1 ± 0.1. Small planet-sized bodies (10^{26} to 10^{27} g, ○) have grown as well as bodies in the lunar-mass range (2.5×10^{25} to 10^{26} g, ●), and a number of small bodies (2.5×10^{25} g, •) have not accreted. The bodies that will become Earth and Venus are not in their present heliocentric positions. In other cases, the early positions of Mars and Mercury were similarly inverted. (b) After 9 million years, 66 percent of the mass (~87 percent of the final radii) has accumulated in the final planets. Two bodies (■) are larger than 10^{27} g, and a number of massive bodies are in rather eccentric orbits. (c) After 252 million years, almost all the bodies have been accumulated into planets with masses and orbits resembling the present terrestrial planets. A few small Mars-crossing bodies remain and are removed by ejection from the solar system, being trapped into asteroidal orbits or planetary collision during the following 250 million years.

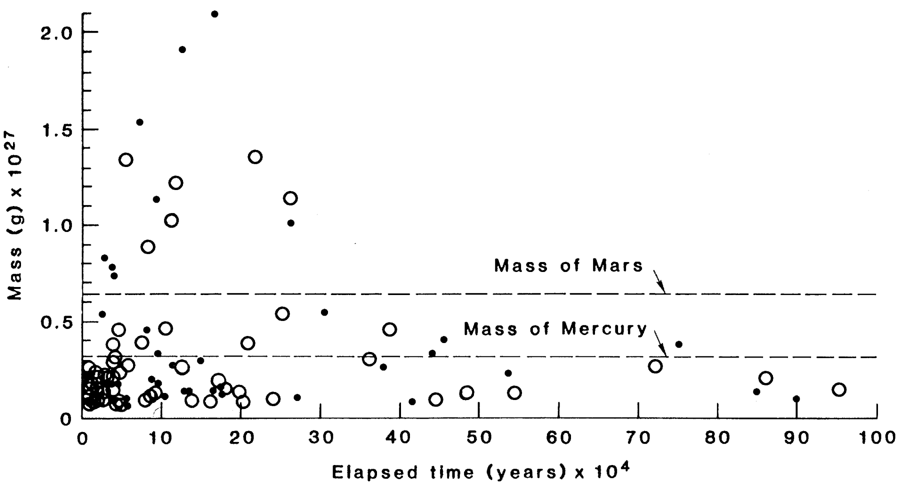

Fig. 2. Time and size of giant impacts on Earth for ten simulations, with (○, five cases) and without (●, five cases) tidal disruption of bodies previously impact-melted (*12*).

cal units (AU) with eccentricities of 10^{-4}, it is expected that during this first stage approximately 4000 bodies about 3×10^{24} g in mass would grow in 10^5 years or less. It proved impractical to use this many bodies in the present calculations. However, it is also reasonable to suppose that as most of the mass began to be concentrated in the larger bodies, the dominant cause of the dynamic evolution would shift away from collisions of small bodies to perturbations by large bodies in orbits of low eccentricity in neighboring zones (*8*). This would cause the eccentricities to increase gradually. When they reach 8×10^{-4}, the zones would be eight times as wide and could contain about 500 bodies of masses in the range of 2.5×10^{25} g (approximately one-third the lunar mass). Most of these calculations were therefore made with 500 initial bodies (density, 3.80 g/cm^3) of this mass as the starting conditions for the final stage of planetary growth. Calculations were also made by means of an integral mass-power law of slope −0.83 (*9*) and bodies from 5.7×10^{24} to 1.13×10^{26} g in mass. The results were insensitive to these initial conditions, and the distinction is not essential to this study.

The late stages of planetary accumulation were simulated by use of a Monte Carlo technique based on that of Arnold (*10*), in which a two-body scattering algorithm is used to calculate mutual planetary perturbations. The validity of using this algorithm in planetary accumulation studies has been investigated by comparison with numerical integration (*8*). On the basis of this work, corrections to the algorithm were made for low values of eccentricity.

In most of these calculations, bodies were distributed in a swarm extending from 0.7 to 1.1 AU, with initial eccentricities randomly distributed between 0 and 0.05 and inclinations between 0 and 0.025, as expected from Safronov's theory (*11*). Semimajor axes were randomly distributed in accordance with a surface density independent of heliocentric distance, to be consistent with the specific orbital angular momentum and energy of the present system of terrestrial planets.

For each successive time step, the probability of each body encountering each other body within a given separation (usually seven gravitational radii) was calculated. The effect of more distant encounters (out to ten Tisserand sphere-of-influence radii) was included by use of the "Arnold extrapolation" (*8, 10*). This probability was used to determine whether a chance encounter occurred between each pair of bodies during the time interval. The separation and geometry of the encounter were chosen at random with proper geometric weighting of distant versus close encounters. Unless collision occurred, the new perturbed orbits were calculated by use of the scattering algorithm. If the encounter distance was less than the gravitational collision radius, a collision was considered to have occurred. The masses of the two bodies were combined, and the new orbit of the combined bodies was calculated. The calculation was continued until only bodies in nonintersecting orbits remained; these were considered as the final terrestrial planets resulting from the simulated planetary accumulation. In addition to collision, bodies were lost from the system (~5 percent) into hyperbolic solar system escape orbits (assisted by Jupiter) during the later stages (≥2 times 10^7 to 2×10^8 years) of accumulation. In principle, material could also be lost by collisional fragmentation, rotational instability, or tidal disruption. At the collisional velocities calculated, loss by fragmentation and rotational instability was unimportant. Recent work (*12*) shows that tidal disruption was also a minor effect.

A calculation of planetary accumulation for which the outcome resembled the present distribution of terrestrial planets (Fig. 1) showed that, during the first 1.8 million years, mutual perturbations increased eccentricities to values as high as 0.2. After 9.4 million years, two bodies with masses greater than 3×10^{27} g and with relatively low eccentricities (about 0.03 or less) and inclinations (<3°) formed, in addition to a large number of bodies with masses in the range of 10^{26} to 10^{27} g (the size of Mercury or Mars). At this stage, 71 percent of the final mass of Earth accumulated. During the last stages of accumulation, requiring up to 2×10^8 years, almost all these intermediate mass bodies, including failed planets with masses greater than 3×10^{26} g, collided and merged with the two bodies in orbits similar to those of the present Earth and Venus. These collisions constituted giant impacts on these planets.

This calculation was one of ten that were made with the same initial conditions but with different Monte Carlo random numbers. The outcome did not usually resemble the present distribution of terrestrial planets as well as that shown in Fig. 1. Except for occasional small bodies in asteroidal orbits, however, in all these calculations the final number of terrestrial planets was limited to either three or four. In three cases, two of the bodies were greater than 10^{27} g in mass, as in the present solar system. In the other seven cases either Mars or Mercury was too large by a factor of 2 to 4. In one case a small planetesimal of one-third the lunar mass survived in an orbit between Earth and Venus. It may be that these various outcomes are characteristic of the chaotic nature of planetary accumulation and that our present terrestrial planet system is but one of many possibilities. If the initial swarm was too spread out (for example, between 0.4 and 1.4 AU), there was a tendency for an excessive number (five to six) of terrestrial planets, approximately equal in mass to one another, to form. Initial swarms this wide are not compatible with the observed energy and angular momentum of the planets for any simple power-law relation between semimajor axis and surface density.

The phenomenon of giant impacts is common to all these calculations, regardless of the details of the final state (Fig.

2). Furthermore, this phenomenon was insensitive to the details of the initial state (for example, bodies of equal size versus a power-law distribution, initial eccentricities as low as 10^{-3}, or number of initial bodies). Inclusion of tidal disruption after close encounters to an extent considerably greater than that permitted (*11*) also did not affect this conclusion. For these reasons it is believed that if terrestrial planets accumulated from smaller bodies (at least if gas drag can be ignored), this accumulation was accompanied by the impact of very large bodies. In the case of Earth, the mass of these bodies was up to three times that of Mars.

The dominance of these large impacts during the growth of Earth (and Venus) may be expected to have important consequences.

1) The kinetic energy ($\sim 5 \times 10^{38}$ ergs) released in the largest impacts (1.5×10^{27} g at ~ 9 km/sec) would be several times greater than that required to melt the entire Earth. Collisions of this size would be highly inelastic. Because the mass of the impacting body is comparable to that of the target, this energy would be distributed over a large fraction of the total volume of the resulting combined body. As a result of these largest impacts, in combination with many more smaller but still massive impacts, as Earth grew it would have been at least partially melted throughout. Core formation by gravitational segregation of metallic iron would proceed simultaneously with the growth of Earth and would not represent a separate later event.

2) It is likely that major quantities of both Earth and the largest projectile would vaporize and recondense in geocentric orbit (*13*). This may have been sufficient to form the moon and could account in a natural way for the large angular momentum of the Earth-moon system, a result that would have been difficult to achieve if the accumulation had been dominated by small bodies of near zero average angular momentum (*1*, *13*). This may also explain chemical differences and similarities between Earth and the moon (*14*). The absence of a moon of Venus could have resulted from possible tidal evolution histories that gave rise to either escape into heliocentric orbit or impact with Venus (*15*).

3) These giant impacts also would have removed a primordial terrestrial atmosphere, even one considerably larger than our present atmosphere (*16*). This raises the possibility that the difference in the content of inert gases of Earth and Venus could simply reflect differences in the gravitationally captured atmosphere in equilibrium with the greatly depleted solar nebula at the time of the last atmosphere-removing impact. The xenon-formation age of Earth's atmosphere ($\sim 10^8$ years) may also date this event in some general way (*17*).

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Expression of the Major Surface Antigen of *Plasmodium knowlesi* Sporozoites in Yeast

Abstract. *The circumsporozoite protein, a surface antigen of the sporozoite stage of the monkey malarial parasite* Plasmodium knowlesi, *was expressed in the yeast* Saccharomyces cerevisiae *by using an expression vector containing the 5′ regulatory region of the yeast alcohol dehydrogenase I gene. It was necessary to eliminate the entire 5′ upstream region of the parasite DNA to obtain the expression of this protein. Only the circumsporozoite precursor protein was produced by the yeast transformants, as detected by immunoblotting. About 55 and 20 percent of the circumsporozoite protein produced in yeast was associated with the 25,000*g *and 150,000*g *particulate fractions, respectively. The protein could be solubilized in Triton X-100 and was stable in solubilized extracts.*

Radiation-attenuated *Plasmodium* sporozoites confer protective immunity against malaria in a number of animal species (*1*). The major sporozoite surface protein, the circumsporozoite (CS) protein, has been implicated as the protective antigen (*2*, *3*). We earlier reported the cloning of the CS gene from the simian malarial parasite *Plasmodium knowlesi* (*4*, *5*), and this opened the way to obtain quantities of the CS protein by expression in suitable host systems. The original *Escherichia coli* construction containing the *P. knowlesi* CS gene expressed the surface antigen as the β-lactamase fusion protein (*4*). For structural and vaccination studies, however, it is important to express the CS gene as a complete protein, with little or no difference from the parasite protein. Recently we reported (in collaboration with the NIH group of B. Moss) the construction of a recombinant vaccinia virus that expresses the complete *P. knowlesi* CS protein in infected monkey cell line CV-1 (*6*). The recombinant virus is antigenic in rabbits, and its vaccine potential is under evaluation. However, whether such a recombinant vaccinia virus vaccine would be safe and effective in humans is not known (*7*). Among the possible options, recombinant yeast appears to be a safe source of antigen and has been successfully used to produce a vaccine effective against the hepatitis B virus infection (*8*, *9*). Here we describe the expression of the complete CS protein of *P. knowlesi* in the yeast *Saccharomyces cerevisiae*, as obtained with an expression vector containing the 5′ regulatory region of the yeast alcohol dehydrogenase I gene.

The CS protein–encoding sequence used was isolated on an Aha III–Aha III fragment of 1.6 kilobase pairs (kb) present in the λkm15 clone, originally isolated from a *P. knowlesi* merozoite DNA Charon 4A library (*5*). It was necessary to eliminate as much as possible the 5′ upstream region of the CS gene sequence