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INVITED REVIEW

Similar-sized collisions and the diversity of planets

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ABSTRACT

It is assumed in models of terrestrial planet formation that colliding bodies simply merge. From this the dynamical and chemical properties (and habitability) of finished planets have been computed, and our own and other planetary systems compared to the results of these calculations. But efficient mergers may be exceptions to the rule, for the similar-sized collisions (SSCs) that dominate terrestrial planet formation, simply because moderately off-axis SSCs are grazing; their centers of mass overshoot. In a "hit and run" collision the smaller body narrowly avoids accretion and is profoundly deformed and altered by gravitational and mechanical torques, shears, tides, and impact shocks. Consequences to the larger body are minor in inverse proportion to its relative mass. Over the possible impact angles, hit-and-run is the most common outcome for impact velocities v_{imp} between $\sim$1.2 and 2.7 times the mutual escape velocity v_{esc} between similar-sized planets. Slower collisions are usually accretionary, and faster SSCs are erosive or disruptive, and thus the prevalence of hit-and-run is sensitive to the velocity regime during epochs of accretion. Consequences of hit-and-run are diverse. If barely grazing, the target strips much of the exterior from the impactor—any atmosphere and ocean, much of the crust—and unloads its deep interior from hydrostatic pressure for about an hour. If closer to head-on ($\sim$30–45°) a hit-and-run can cause the impactor core to plow through the target mantle, graze the target core, and emerge as a chain of diverse new planetoids on escaping trajectories. A hypothesis is developed for the diversity of next-largest bodies (NLBs) in an accreting planetary system—the bodies from which asteroids and meteorites derive. Because nearly all the NLBs eventually get accreted by the largest (Venus and Earth in our terrestrial system) or by the Sun, or otherwise lost, those we see today have survived the attrition of merger, evolving with each close call towards denser and volatile-poor bulk composition. This hypothesis would explain the observed density diversity of differentiated asteroids, and of dwarf planets beyond Neptune, in terms of episodic global-scale losses of rock or ice mantles, respectively. In an event similar to the Moon-forming giant impact, Mercury might have lost its original crust and upper mantle when it emerged from a modest velocity hit and run collision with a larger embryo or planet. In systems with super-Earths, profound diversity and diminished habitability is predicted among the unaccreted Earth-mass planets, as many of these will have be stripped of their atmospheres, oceans and crusts.

1. Introduction

During the late stage of terrestrial planet formation (Wetherill, 1985), giant impacts occur when similar-sized planets at or near the largest end of their size distribution collide at speeds ranging from $\sim$1 to a few times their mutual escape velocity v_{esc}. This notion of late giant impacts emerged alongside the idea for a giant impact origin of the Moon (Hartmann and Davis, 1975), where a Mars-sized projectile is proposed to have struck the proto-Earth to liberate a new planet composed mostly of Earth-like mantle. Giant impacts can be generalized as occurring between the largest and next-largest bodies at any stage of planet formation, at impact velocities v_{imp} comparable to the mutual escape velocity

$$v_{esc} = \sqrt{2G\frac{M+m}{R+r}} \tag{1}$$

which is the velocity at which two spheres collide if starting out at zero velocity at infinite distance. The radii $r \lesssim R$ and masses m and M correspond to a spherical projectile and target, and $G = 6.673 \times 10^{-8}\,\text{cm}^2\,\text{g}^{-1}\,\text{s}^{-2}$. This generalization of giant impact is called a similar-sized collision or SSC.

Agnor and Asphaug (2004a) studied collisions between equal-sized planetary embryos (r=R) and found that merger is inefficient except when v_{imp} almost equal to v_{esc}. Impact speeds are expected to be higher than this in the late stage of terrestrial planet formation, since the orbits must be planet-crossing. This paved the way to studies (Asphaug et al., 2006) of geophysical and compositional

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evolution in a broader range of scenarios ($r \lesssim R$). They found that it is common in gravitationally stirred-up populations for planetary embryos somewhat smaller than the largest to dash up against the largest but not accrete. These hit and run collisions dismantle the impactors (r) or catastrophically disrupt them in peculiar ways.

It is argued below that many or most of the unaccreted next-largest bodies (NLBs) surviving the late stage of planet formation bear the scars of one or more hit and run collisions. A remarkable diversity is then predicted for the final collection of NLBs, whether they be Mars and Mercury of the inner solar system, middle-sized members of Saturn's satellites, Vesta and Psyche in the Main Belt, Quaoar and Haumea and other oddities beyond Neptune, or Earth-mass planets in solar systems with super-Earths. Next-largest bodies are lucky to be here, and each is lucky in its own way.

Hit-and-run can be as common as accretion, when the characteristic random velocity v_∞ of a planetesimal swarm (relative to distant circular coplanar orbits) is comparable to the characteristic escape velocity v_{esc} of the largest members of the population. This random velocity is added to the escape velocity, so that spherical planets collide at an impact velocity

$$v_{imp} = \sqrt{v_\infty^2 + v_{esc}^2} \tag{2}$$

When random velocity $v_\infty / v_{esc} \simeq 0$ accretion is efficient, but when $v_\infty \approx v_{esc}$ hit and run is the most common outcome. The unique petrogenetic outcomes of hit and run collisions, and the predicted diversity of NLBs and the asteroids and meteorites that derive from them, may be indicative of the random velocities that prevail during the dynamical epochs of planet formation, in the earliest stages corresponding to the evolution of chondrites and chondrules, and in the late stages that define the characters of finished planets.

1.1. Accretion basics

In the classical accretion theory of Safronov (reviewed in Wetherill, 1980) the random velocity is related to the escape velocity, regulated by the gravitational stirring, according to

$$\Theta = \frac{v_{esc}^2}{2v_\infty^2} \tag{3}$$

The Safronov number Θ is postuated to be $\sim 3-5$ during the course of planetesimal growth (Safronov and Zvjagina, 1969; Safronov, 1972) and closer to $\Theta \approx 1-2$ in the late stage of terrestrial planet formation (Wetherill, 1976). This relation arises from the assumption of planetesimal (gas-free) accretion, with random velocities excited gravitationally by the largest bodies into mutually crossing orbits. Based on N-body numerical experiments, Agnor et al. (1999) and O'Brien et al. (2006) find that v_{imp} ranges from >1 to a few times v_{esc} during the late stage of giant impacts, broadly consistent with Wetherill's result.

The ratio $v_\infty / v_{esc} = \sqrt{1/2\Theta}$ depends on the location within the size distribution, since v_{esc} and random velocity both change. The ensemble gravitational drag of small planetesimals reduces the velocity dispersion of the larger embryos, so generally v_∞ is lower for steeper mass distributions (with greater masses of small particles). If gravitational stirring happens to small and large bodies alike, then smaller bodies encounter one another at higher v_∞ / v_{esc}, so even if the largest encounters are mostly accretionary ($v_\infty / v_{esc} \sim 0.3$, say), colliding bodies half as large will have $v_\infty / v_{esc} \sim 0.6$, with outcomes that are mostly hit-and run. This is why hit and run is described below as an edge effect, occurring at the margin of the population.

Under dynamically cold conditions ($v_\infty \ll v_{esc}$) the growth of the largest bodies can run away (Greenberg et al., 1978; Weidenschilling, 2008) since the rate of growth dR/dt increases with R. This is because growing bodies sweep up small planetesimals within an enhanced cross-sectional area that is increased by a gravitational focusing factor

$$F_g = 1 + 2\theta = 1 + \frac{v_{esc}^2}{v_\infty^2} \tag{4}$$

accounting for slow planetesimals falling in towards the body. The other scenario, $v_\infty \gg v_{esc}$ is sometimes called orderly growth; since there is no focusing all bodies increase in radius at the same rate. But orderly growth assumes perfect sticking during a sweep-up of planetesimals at high random velocity. Perfect sticking can be a very poor assumption when $v_\infty \gg v_{esc}$, and this calls to question whether orderly growth is a valid concept.

Planet formation is likely to involve quiescent epochs, and also epochs of moderate random stirring dominated by similar-sized collisions. It seems incontrovertible that moderate random velocities are required during the late stage, since orbits must intersect across increasing distances. Epochs of random stirring are also expected during the first few million years of solar system formation. The severe consequences of planetary dismantling by the mechanism of hit-and-run are likely to be vital to the final bulk chemistry of planets. Planetary growth is after all not just the accumulation of a feeding zone by accretionary events; it is also the record of a comparable or even greater number of non-accretionary hit-and-runs, each with the capacity to dismantle and segregate a next-largest body's mantle, core, atmosphere, crust and ocean.

1.2. Collision timescale

Collisions involving bodies within a factor of 2–3 in size are extended-source phenomena, distinct in important respects from the point-source collisional phenomena that cause the formation of impact craters (Melosh, 1989). A key difference is that there is no physically important central point in a similar-sized collision—broad regions such as the cores respond in one way, and the colliding mantles respond in another. The outer layers (atmosphere, ocean, crust) respond in yet another. The impact locus as it were is hemispheric or even global in extent. The understanding of impact cratering benefits greatly from the principle of late stage equivalence, a strong form of hydrodynamic similarity whereby the fundamental characteristics of a collision are obtained by geometric (power law) combinations of impactor radius, density and velocity (Holsapple, 1993). In cratering this allows meaningful extrapolations of laboratory results to large geophysical scales. Hydrodynamical similarity applies to SSCs, but not the cratering concept of an impact locus.

A second major distinction between similar sized collisions and impact cratering is that the contact and compression timescale for an SSC equals the gravity timescale. The smaller planet is deformed mechanically (compressed and sheared) by its abrupt deceleration against the target, while it is deformed gravitationally. Its fate, and the outcome of the collision, may depend upon the inter-dominance of self-gravitational instability and shear instability. The deceleration and deformation of the projectile in a head-on collision occurs on a timescale

$$\tau_{coll} = 2r / v_{imp} \tag{5}$$

where v_{imp} is the collisional speed at the time of contact. Because $v_{imp} \sim 1$ to a few times v_{esc}, the collisional timescale for SSCs is $\tau_{coll} \sim r / v_{esc}$. By comparison, the self-gravitational timescale is

$$\tau_{grav} = \sqrt{3\pi / G\rho} \tag{6}$$

where the density $\rho = M / \frac{4}{3}\pi R^3 = m / \frac{4}{3}\pi r^3$ assuming uniform bodies. This is the time for a sphere of uniform-density matter to orbit itself. Because $r \sim R$ for similar-sized bodies,