Growth and Evolution of Asteroids

Erik Asphaug

Department of Earth and Planetary Sciences, University of California Santa Cruz, Santa Cruz, California 95064; email: easphaug@ucsc.edu

Key Words

planet formation, planetesimals, small bodies, accretion, NEOs

Abstract

Asteroids are what is left of the precursors to the terrestrial planets. They are stunning in their diversity, ranging from charcoal-black worlds the size of a hilltop, spinning like a carnival ride, to dog-bone-shaped metallic remnants of some cataclysmically disrupted planetary core, to worlds as stately as Ceres and Vesta (and fragments thereof), to garden-variety fractured and blocky nuggets that dominate near-Earth space. Asteroid belts are common around Sun-like stars. When properly seen as unaccreted residues, as scraps on the floor of the planetary bakery, the diversity of asteroids can be fully appreciated, for to paraphrase Tolstoy, accreted planets are all alike; every unaccreted planet is unaccreted in its own way.
1. ASTEROID BASICS

Asteroids are small rocky planetary bodies. Like many definitions in planetary science, this one has outliers and exceptions. It is also vague: small is not well defined, and rocky takes on a variety of geochemical and rheological meanings. But these concepts serve as an outline for the study of asteroids, because understanding small is to characterize the transition from one realm of geophysics to another—asteroids straddling the two—while describing rocky is to address some of the fundamental aspects of meteoritics, itself a venerable discipline in search of geologic context.

Sometimes asteroids are equated with planetesimals, which are the building blocks of terrestrial planets. But this definition applies only insofar as asteroids are primordial. Nearly every asteroid we see today, whether of primitive or evolved composition, is the product of a complex history involving accretion followed by one or more episodes of catastrophic disruption. Energetic collisions among asteroids, in the aftermath of planet formation, have resulted in dynamical families of smaller asteroids, most of them now mixed into the background population, but all with distinct and indicative petrogenic relationships. Dozens, perhaps hundreds, of early asteroids grew large enough to thermally differentiate, leaving scattered pieces of their metal-rich cores and, more rarely, their mantles and crusts.

Asteroids represent stages on the rocky road to planet formation. Most of the matter that survives from the original protoplanetary disk is bound into planets. But the unaccreted small bodies of the terrestrial planet forming region—the asteroids—are fated to wander the solar system at the whims of the larger dynamical bodies. They have stories to tell.

1.1. Primitive Bodies

The study of asteroids has emerged as one of the most active research areas in planetary science. One reason for this is the novel context of near-Earth space, where many asteroids reside, transported from much larger populations elsewhere in the solar system. Another is the utility of asteroids as tracers of the past history of planetary evolution: Having borne witness to the solar system’s origin, they are like fossils to a paleontologist.

Every day, hundreds of tons of asteroidal fragments rain down on Earth, mostly in the form of micrometeorites and sand- to pea-sized grains (shooting stars), few of which reach the ground. Those that do mostly go undiscovered except when they land on rock-free deserts or ice sheets, or are witnessed falling. Space missions are under way, and others planned, to bring back samples from asteroids in order to make a rigorous connection between solar system origins, planetesimals, planets, and the hundreds of tons of meteorites that are found on Earth.

The largest meteorites are too massive to transport. The 60-ton Hoba meteorite is a $\sim 1 \times 3 \times 3$ m tabloid of iron (a IVB nickel-rich ataxite) that sits where it landed 80,000 years ago in Namibia. It is larger than the smallest asteroids observed in modern observational campaigns. This has rendered the distinction between asteroids and meteoroids arbitrary; 50 m is often applied as the cutoff.

By number, the population of asteroids is dominated at the smallest sizes, approximated by a power law

$$n(D) = C D^{-\alpha},$$

where $n(D) \, dD$ is the number of bodies in the size range $D$ to $D + dD$, and $C$ and $\alpha$ are positive constants, with $\alpha$ typically around 3 (see below). This means that small asteroids are far more numerous than large ones, whereas large asteroids possess most of the mass. A major struggle in the science of asteroids is therefore to define what is typical: the innumerable rocks in space larger
Typical asteroids? Itokawa, Eros, Mathilde, and Vesta span a factor of 1000 in size. The Vesta image is a computer model based on HST data (B. Zellner, P. Thomas, and NASA/HST). Mathilde and Eros images are from the NEAR mission (NASA/JPL/JHUAPL). Itokawa image is from the Hayabusa mission (ISAS/JAXA). Ceres, Vesta, and a couple of other planetoids contain half the mass of asteroids, while small bodies like Itokawa are the most typical and dominate near-Earth space.

than 50 m, or the handful of main-belt planets like Vesta and Ceres, which contain most of the mass (see Figure 1).

Large asteroids are weighed from their perturbations on Mars and on each other (Williams 1984, Michalak 2000). Krasinsky et al. (2002) derived the total mass of the asteroid belt by analyzing the motions of the major planets, processing high-precision ranging information relative to the Viking and Pathfinder landers over a 21-year period. They modeled the 300 largest asteroids and the major planets directly, and the residual gives the remaining mass of the belt. According to their studies, the total main-belt mass is $\sim 1.8 \times 10^{-9} M_\odot$, where $M_\odot$ is the mass of the sun; thus $\sim 3.6 \times 10^{21}$ kg is the total mass of asteroids according to this study. That is four times the mass of Ceres, $\sim 0.6\%$ the mass of Mars, and $\sim 5\%$ the mass of the Moon.

Asteroids are incredibly diverse. If gravity is the discriminant, then Itokawa is expected to be as different from Eros, geologically, as Eros is from the Moon (see Table 1). Asteroid gravity varies by more orders of magnitude than its variation among the terrestrial planets, including the Moon. Composition also varies, from ice-rich to lunar-like to chondritic. Why do we lump Eros and Itokawa into the same bin? Mathilde and Vesta? What do asteroids have in common? This is a time to go exploring.

Each rendezvous with an asteroid has turned our geological understanding on its head, with relevance close to home in areas of granular mechanics, landslides, earthquakes, faulting, and impact cratering. Asteroids serve as important scale analogues, with the physics appearing familiar, but with $g$ varying from $< 10^{-5} g_\oplus$ for the smallest asteroids to $\sim 1/30 g_\oplus$ for Ceres and Vesta, where $g_\oplus$ is the surface gravity of Earth.

One remarkable discovery of the past several years is that asteroids are commonly found in double- and even triple-systems. This places them in the center of debates regarding the origin

Chondritic: refers to an asteroid or meteorite composition that is undifferentiated from the condensable solid component of the original protoplanetary nebula (also known as solar composition)
Table 1  Gravity of some typical asteroids, compared with Vesta and the Moon

<table>
<thead>
<tr>
<th>Asteroid or planetoid</th>
<th>Diameter (km)</th>
<th>Gravity (cm/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Itokawa</td>
<td>0.33</td>
<td>~0.01</td>
</tr>
<tr>
<td>Eros</td>
<td>20</td>
<td>~0.4</td>
</tr>
<tr>
<td>Vesta</td>
<td>530</td>
<td>~22</td>
</tr>
<tr>
<td>Moon</td>
<td>3474</td>
<td>162</td>
</tr>
</tbody>
</table>

of planets such as the Earth and Moon, or Pluto and Charon, although the processes of asteroid binary formation are likely to be different. Because a binary asteroid is not quite accreted, studies of binary and multiple-system mechanics are of great relevance to understanding the earliest stages of planet formation. Observations of binary asteroids, and of fast-spinning single asteroids, have taught us that many teeter at the brink of mechanical stability.

Taken in a broader context, asteroids are important players in the cosmic universe. There are planets everywhere, and massive asteroid belts have been detected in the terrestrial planet-forming regions around a significant fraction of young Sun-like stars. Meyer et al. (2008) use the Spitzer Space Telescope to detect 24 µm mid-infrared emissions indicative of debris disks and identify disks around 18% of stars ~3 to 30 Ma in age, 12% of stars ~30 to 300 Ma in age, and 2% of stars ~0.3 to 3 Ga in age. At least approximately one-third and as many as two-thirds of Sun-like stars in the survey exhibit this evidence for terrestrial planet formation.

The fact that disks become less common with stellar age, on a timescale of ~100–300 Ma, implies a timescale for disk clearing that is compatible with what is known from theoretical studies of terrestrial accretion, presented in Section 3.2. As far as we understand that epoch in our own solar system, what happened here appears to be happening there. If it were not for asteroids bumping into one another, with accretion winning out over disruption, there would not be terrestrial planets, nor perhaps life as we know it.

Nearly all of our original protoplanetary disk has cleared away; asteroids are residuals in pockets of dynamical stability. Figure 2 plots all major and minor planet locations as they appeared at the time of writing. The main-belt asteroids (MBAs) are the dominant population, forming a broad torus where a planet might have formed had Jupiter not been where it was. A couple of other important classes can be distinguished, including the near-Earth asteroids (NEAs) around 1–1.5 AU and the Trojan asteroids leading and trailing Jupiter that are categorized as asteroids but may be cometary in composition.

Comets are not specifically a subject of this review (see Weissman et al. 2004, Luu & Jewitt 2002), although there are more similarities than differences (Figure 3). A dynamical distinction between asteroids and comets is available in the context of the restricted 3-body problem, with the Sun and Jupiter as the primary masses. For a small body (test particle) encountering a planet in circular orbit about the Sun, the Tisserand parameter

\[ T_P = \frac{a_P}{a} + \frac{2}{\sqrt{1-e^2}} \sin i \]  

is a dynamical quantity that is approximately conserved before and after the encounter, where \( a_P \) is the semimajor axis of the planet and \((a, e, i)\) are the semimajor axis, eccentricity, and inclination of the asteroid or comet. \( T_P \) also gives the relative velocity between a small body and a planet during close encounters, \( v_{rel} = \sqrt{3-T_P} \), where \( v_P \) is the planet’s orbital velocity about the Sun.

Objects with \( T_P > 3 \) are not planet-crossing. Comets are therefore often defined dynamically as having \( T_J < 3 \) (\( J = \) Jupiter), with Jupiter-family comets (JFCs) having \( 2 < T_J < 3 \) and long-period
Figure 2

Inner solar system diagrams showing the positions of all numbered asteroids and comets on October 1, 2008. The orbits and positions of Mercury, Venus, Earth, Mars, and Jupiter are shown; the Trojan, main-belt, Hilde, and near-Earth asteroid populations are evident. Asteroids are yellow dots and comets are sunward-pointing wedges. The top diagram is plotted from above the ecliptic plane (the plane containing the Earth’s orbit), whereas the bottom diagram is plotted from the edge of the ecliptic plane. In both diagrams, the vernal equinox is to the right, along the horizontal axis. Figure courtesy of Paul Chodas (NASA/JPL).
Figure 3

Two periodic cometary nuclei and the only primitive asteroid imaged to date. Figure of comet 81P/Wild 2 (left) from the Stardust mission; figure of comet 9P/Tempel 1 (center) from the Deep Impact mission; figure of asteroid 253 Mathilde (right) from the NEAR mission (NASA images). All are dark, low-density bodies. Mathilde is much larger than the comets (D = 53 km); no cometary nucleus larger than ~10 km and no primitive asteroid smaller than Mathilde has been clearly imaged; a mission to a ~1–10 km primitive asteroid is a scientific priority. The largest comets have appeared irregular (1P/Halley, 19P/Borrelly), whereas the smaller comets have appeared relatively spheroidal—opposite to the trend observed so far for asteroids.

and Halley-type comets having $T_J < 2$. The distinction is illustrative and useful, since it preserves populations that get scattered by Jupiter.

Comets are also defined compositionally as being ice-rich as opposed to rocky and specifically, as capable of developing a coma if it comes close to the Sun. But the dynamical and compositional definitions do not always coincide. Recent observations have revealed water ice in the spectra of a number of the asteroids of the outer main belt; Hsieh & Jewitt (2006) have adopted the term main-belt comets (MBCs) for such objects, some which exhibit comae. Bottke et al. (2002b) calculate on the basis of dynamical integrations that 6 ± 4% of NEOs (near-Earth objects) are extinct Jupiter-family cometary nuclei.

How ice-rich must an asteroid be to be a comet? A geological distinction between comets and asteroids might be available on the basis of the response to impact cratering, analogous to glaciology, where a rock pile with an ice fraction of only a few percent can be called a glacier on the basis of rheology. A characterization of large impact structures might thus distinguish comets from asteroids when their spectra and potential for activity don’t give them away.

Comets are orders of magnitude more abundant in the solar system than asteroids. The total mass of the main belt is only ~5% the mass of the Moon, according to calculations of gravitational influence by Krivosky et al. (2002), or ~4 times the mass of Ceres. The total mass of comets in the Edgeworth-Kuiper belt (the cometary equivalent of the main belt, between 30 and 50 AU) is hundreds of times greater, estimated at ~5–20 lunar masses (Jewitt et al. 1998), most of it in a collection of Pluto-sized bodies. The “scattered disk” of comets contains an additional ~4–40 lunar masses (Luu et al. 1997, Trujillo et al. 2000). To this we add the Oort cloud, which has been estimated at ~1 Earth mass (e.g., Stern & Weissman 2001) or even more.

Despite representing orders of magnitude more material, comets occupy a proportionately larger volume of space. They are sparsely distributed and orbit the Sun much less frequently than asteroids. The timescale of collisional evolution of asteroids is thus orders of magnitude faster. While as many as ~100 or more short-period JFCs like 3552 Don Quixote and 1997 SE5 have

NEOs: near-Earth objects, including comets, asteroids, and all other small objects that have perihelion q ⩽ 1.3 AU and may collide with Earth.
ended up in near-Earth space, they are anomalous; the NEO population is dominated by the rocky objects that are more readily delivered from the main belt.

### 1.2. Asteroid Populations

The largest repository of asteroids is the main belt between the orbits of Mars and Jupiter. MBAs are bounded by two mean-motion resonances with Jupiter, the 5:1 at 1.78 AU and the 2:1 at 3.28 AU (see Figure 6). The NEAs leak inwards from the main belt on a timescale of tens of millions of years (Morbidelli et al. 2002) and comprise an ongoing dynamical sampling of MBAs.

There is a systematic size bias between NEAs and MBAs. Smaller asteroids are more easily dislodged from the main belt, owing to the strongly size-dependent, and surprisingly important, Yarkovsky nongravitational force described below. This radiation force can cause a sub-kilometer asteroid to migrate an astronomical unit or more, but it is generally negligible for asteroids larger than ∼10 km. Yarkovsky migration causes the leakage of asteroids into nearby mean-motion resonances and secular resonances, at which point their orbits are gravitationally destabilized by the action of major planets (Vokrouhlický & Farinella 2000).

#### 1.2.1. Size distribution.

There are one or two million MBAs, and a thousand NEAs, larger than 1 km. Their size distribution \( n(D) \) is well approximated by a power law or segmented power law, derived from the cumulative number \( N \) of asteroids larger than \( D \). The derivative \( \frac{dn}{dD} = CD^{-\alpha} \), where \( \alpha \geq 0 \). This is equivalent to a power law mass distribution: \( m \propto D^3 \) and \( dm \propto D^2 dD \), so \( \frac{dN}{Bm^{-(\alpha+2)/3}}dm \). Because cumulative, differential, and mass and size distributions are all sometimes reported, it is important to be familiar with their conversion.

For the main belt, a Subaru telescope survey by Yoshida & Nakamura (2007) obtains \( \alpha \simeq 2.3 \) for asteroids \( D < 1 \) km, transitioning to \( \alpha \simeq 2.7 \) for larger sizes. Sloan Digital Sky Survey commissioning data indicate a slope \( \alpha \simeq 2.3 \) for \( 0.4 \) km < \( D < 5 \) km, transitioning to a steep \( \alpha \sim 4 \) for \( D > 5 \) km (Ivezic et al. 2001). The break in slope at \( D \sim 5 \) km can be regarded as a broad “bump” as it shallows out again for \( D > 20 \) km. Differences between surveys may be due to alternate approaches in mapping magnitudes to MBA diameters.

For small NEAs, the size distribution is steep. Brown et al. (2002) report \( \alpha = 3.7 \) in the range \( 0.1 \) m < \( D < 200 \) m, based on satellite detection of large fireballs extrapolated to telescope results; this is not far from the case \( \alpha = 4 \) of equal mass in equal logarithmic bins described below. This steep NEA size distribution is likely the result of the physics that delivers them to near-Earth space—impacts that create numerous small asteroids at the expense of large ones and dislodge the small ones the fastest, and the nongravitational Yarkovsky force that preferentially mobilizes small members of the population.

Assuming that the 1908 Tunguska explosion was an event with energy \( \sim 10 \) Mt, the mean recurrence interval of such events on Earth is estimated by Brown et al. as \( \sim 1000 \) years, although the frequency of large fireballs is a topic of great controversy.

#### 1.2.2. Comminution and disruption.

The power-law characteristics of rock comminution (Gaudin 1939) is applicable to asteroids. One can write

\[
\log p = k \log D + \log A,  \tag{3}
\]

where \( p \) is the percentage of the total mass contained in asteroids with diameters between \( D_1 \) and \( D_2 \), and \( k \) and \( A \) are constants (Hawkins 1960). \( D \) is the geometric mean diameter between logarithmic size limits, and \( p \) is the mass found in incrementally finer sieves. The mass in an interval \( dN \) is \( m\Delta N = Bm^{(1-\alpha)/3} dm \), and the mass between \( D_1 \) and \( D_2 \) is found by integrating; assuming

---

**Mean-motion resonance**: when two bodies orbiting a massive central body exert a periodic gravitational influence on one another due to their mean motions (orbital frequencies) being the ratio of two small integers

**Secular resonance**: a periodic gravitational influence that occurs when the rates of precession of the orbits of two bodies about a massive central body are synchronous.
a uniformly logarithmic interval $D_{i+1} = \beta D_i$, one obtains $p = AD^{4-\alpha}$, so $k = 4-\alpha$. Thus, when $\alpha = 4$, there is equal mass in every logarithmic size interval; in the case of steady-state comminution $\alpha < 4$, there is more mass at larger size intervals.

Experiments reported by Gaudin (1939) of quartz rocks ground in a rock mill have $\alpha \approx 3$ early on and end with $\alpha = 3.5$ after 10 h. In a landmark paper applying disruption physics to asteroids, Dohnanyi (1969) examined collisional cascades in which the products of asteroid disruption become impactors responsible for further asteroid disruption. Assuming that disruption physics is invariant with size, any reasonable starting population was found to relax to $\alpha = 3.5$.

But the comminution of asteroids involves more complicated physics than the grinding of rocks in a mill. The exterior of an asteroid is pummeled while the interior is sheltered, for instance, and the whole mass is cratered, comminuted, and vibrated episodically. Eventually an asteroid suffers the fatal blow that sends its pieces asunder, forming asteroid families. The recipe is one part geophysics, one part astrophysics.

The assumption of a self-similar collisional cascade is a poor (but useful) one because the dominant physics changes at the size of typical asteroids. Asteroids $D \lesssim 1$ km appear to be governed by structural and mechanical forces, and larger asteroids by self-gravitation. These are the strength and gravity regimes discussed further below, which have opposite trends in terms of effective impact strength. Even within each regime it is not sure that self-similarity applies.

Mechanical strength varies considerably with size and strain rate. Static strength decreases with size, because there are larger irregularities in a larger rock. Strain rate also decreases with the size scale of a collision, further diminishing the dynamic strength (summarized in Asphaug et al. 2002). But the largest asteroids have significant gravitational overburden, leading to increasing impact strength. Because the trends are opposite, the impact strength (measured as $Q^*_D$, the impact kinetic energy per unit mass required to disrupt a body; Davis et al. 1985) is a V-shape plotted versus size, with minimum $Q^*_D$ around $D \approx 100$ m (Figure 4).

The largest asteroids are melted and stratified, further increasing their binding energy by concentrating dense metals at the center. Differentiated asteroids are thus more difficult to disrupt, by a factor of $\sim 3$, than Figure 4 indicates, based on SPH collisional models described below. Another distinction for large planetoids is that they gravitationally focus slow bodies onto collision course, and are thus more heavily bombarded. This is expressed as a gravitationally enhanced cross section that increases the geometric cross section $\pi(D^2/2)$ by a factor $f_g = \left(1 + \frac{v_{esc}^2}{v_\infty^2}\right)^{1/2}$.

Gravitational focusing is significant where random velocities $v_\infty$ are smaller than the escape velocity $v_{esc}$. Although it enhanced the flux of low-velocity bombarding material for large planetoids early on, focusing no longer plays a role in asteroid evolution.

Even in idealized self-similar collisional systems, there are boundary effects associated with the cutoff at the large end (Ceres) and at the small end (dust swept away by the solar wind). Bumps and wiggles in the asteroid size distribution have been attributed to the removal of dust, which would otherwise collisionally disrupt the sand-sized particles. An excess of sand causes gravels to disrupt, and so on. The result is a superposition of waves in an otherwise straight power law (Davis et al. 2002). Similarly, the steep V-shape of Figure 4 may strip out the $D = 100$ m objects that are the most easily disrupted; their efficient removal would enhance the representation of $D \sim 3\text{–}4$-km asteroids (their targets) relative to a straight power law, consistent with the observed size distribution (see Figure 5).

The red curve in Figure 4 derives from simulations beginning with solid unfractured spheres (Benz & Asphaug 1999), probably not a realistic starting condition. The other curves come from
The catastrophic disruption threshold of asteroids is characterized by $Q_\ast D$, the impact kinetic energy per gram of target required to leave behind no remnant (reaccreted or otherwise) larger than half the original mass. Strength diminishes with size owing to size- and rate-dependent strength effects (Asphaug et al. 2002), while beyond $D \sim 100$ m self-gravitational binding catches up, making it increasingly difficult to disrupt massive targets. Figure adapted from Benz & Asphaug (1999), whose numerical result is the dark red curve; other curves (see references therein) are from a variety of published scaling theories and are indicative of the uncertainty in catastrophic disruption theory.

Similarly optimistic assumptions or extrapolations. In reality, asteroids are complex entities whose impact strength properties may have little to do with the physical behavior of laboratory rocks (the strength-scaling assumption) or fluidized spheres (the gravity-scaling assumption). There is much work to be done on the experimental and modeling front (see most recently Leinhardt & Stewart 2008) and in conducting geophysical investigations at asteroids.

1.3. Shaping the Main Belt

Jupiter’s dynamical forcing sculpts the asteroid population, as evident in Figure 2 and Figure 6. The main belt is bounded by the 5:1 and 2:1 mean-motion resonances at 1.8 and 3.3 AU, respectively, where $n/m$ is the ratio of mean motions, the number of times $n$ that the asteroid orbits the Sun for every $m$ times Jupiter does. In between are several clearings and gaps that occur at low-order resonances, most prominently the 3:1 at 2.5 AU (see also Figure 8).

These are the Kirkwood gaps that form when small asteroids migrate into the resonances, which serve as dynamical sinks. Once a small asteroid becomes planet-crossing, its dynamical lifetime is less than a few tens of Ma (Gladman et al. 1997) until it collides with a planet or the Sun, or is ejected. This dynamical leakage is the main pathway from the main belt to near-Earth space, and the force that nudges small asteroids into these resonances is sunlight.
Figure 5
Estimated main-belt asteroid size distribution (Jedicke et al. 2002; figure courtesy W. F. Bottke). The size distributions of minor body populations are sometimes described as straight power laws with bumps and wiggles, or as segmented power laws representing different physical regimes, e.g., different sources and collisional physics.

1.3.1. Yark and YORP. The Yarkovsky effect is a cumulative dynamical force that results from the anisotropic reradiation of thermal photons. On a rotating asteroid, the hotter afternoon hemisphere emits photons with relatively high momentum, \( p = E/c \), where \( E = hv \) is photon energy and \( c \) is the speed of light. Photon emission thus produces a Sun-powered thrust that can move small asteroids by several AU over their history, pushing them into gravitational resonances.

Figure 6
The 156929 asteroids known as of 2007 plotted as a histogram of distance from the Sun. Figure courtesy Alan Chamberlin and the Solar Systems Dynamics group at JPL (http://ssd.jpl.nasa.gov). The Kirkwood gaps are found at the low-order mean motion resonances with Jupiter.
or into collisions with planets. There is also a seasonal Yarkovsky effect, associated with the hotter summer hemisphere.

The Yarkovsky force is computed from an asteroid’s length of day, albedo, thermal inertia, distance from Sun, shape, and photometric phase function. Thermal inertia is usually the largest uncertainty:

\[
\Gamma = \sqrt{\rho c \kappa},
\]

where \(\rho c\) is the volumetric heat capacity and \(\kappa\) is thermal conductivity. The greater the heat capacity, or the greater the conductivity, the more thermal energy a parcel can soak up either by absorbing it or conducting it away; therefore the maximum day/night temperature variation on a planetary surface is greatest for materials with low thermal inertia. For lunar regolith in vacuum \(\Gamma \sim 50 \text{ J s}^{-1/2} \text{ K}^{-1} \text{ m}^{-2}\); for bare rock \(\Gamma \sim 2500 \text{ J s}^{-1/2} \text{ K}^{-1} \text{ m}^{-2}\). The day/night temperature difference that drives the Yarkovsky effect is also related to asteroid size and rotation; very fast rotators and very small asteroids are almost isothermal. The average thermal inertia measured for NEOs is \(\Gamma \sim 300 \text{ J s}^{-1/2} \text{ K}^{-1} \text{ m}^{-2}\) (Delbo et al. 2007), with a trend of higher thermal inertia for smaller asteroids (e.g., 150 s\(^{-1/2}\) K\(^{-1}\) m\(^{-2}\) for Eros, 700 s\(^{-1/2}\) K\(^{-1}\) m\(^{-2}\) for Itokawa). Images of Itokawa appear rocky or gravelly, whereas Eros appears dusty, in agreement with this trend. But no asteroid measured so far has rock-like thermal inertia (\(\Gamma \sim 1000 \text{ s}^{-1/2} \text{ K}^{-1} \text{ m}^{-2}\)). In situ thermal investigations of small asteroids are required to resolve this quandary.

Closely related to thermal inertia is surface roughness, which can be measured directly through laser ranging from orbit, and can be obtained from Earth as the ratio of same-sense to opposite-sense circularized polarization of reflected radar energy. Roughness at the radar wavelength (typically tens of cm) increases the same-sense circular polarization. This SC/OC ratio (Benner 2008) together with thermal inertia provide fundamental information about the surface geology of asteroids, and can be of great aid in mission planning. Interestingly, Eros and Itokawa have about the same decameter-scale radar roughness, although visibly, Itokawa is lacking in dust, and has a roughness derived from laser ranging that is, on average, equivalent to the roughest parts of Eros (Abe et al. 2006).

The Yarkovsky effect (Yark) has been directly measured on small asteroids using radar astrometry (Chesley et al. 2003). The force scales with surface area \(D^2\) so the acceleration scales with \(D^{-1}\), all else being equal. Since bodies with lower thermal inertia have higher diurnal temperature variation, Yark may drop off somewhat more gradually with size, more like \(D^{-0.6}\), if the trend observed by Delbo’ et al. (2007) applies. Yark is thus only significant for asteroids smaller than tens of km. Since this includes the vast majority of asteroids, it has led to significant evolution of the architecture of the solar system and is responsible for the delivery of so many diverse asteroids to near-Earth space and meteorites to Earth.

A companion effect is called YORP (Rubincam 2000), and it is a torque that spins asteroids into fast rotation when the emission of thermal photons has chirality. Like the Yarkovsky effect, YORP depends on the asteroid’s shape, albedo, rotation, heliocentric distance, and material thermal parameters. Even an isothermal asteroid can experience this radiative torque. Change in spin by YORP has been directly measured (Lowry et al. 2007, Taylor et al. 2007) and is spinning up some small asteroids on \(\sim 10^3\) year timescales. According to Rubincam (2000), an asteroid as large as 10 km might double (or halve) its rotation rate every few hundred million years. Because YORP like Yark, scales with \(\sim 1/D\), the spin rate of a small asteroid like namesake 54509 YORP (\(D \sim 100\) m),
Asteroid 617 Patroclus (left) is the first known binary Trojan asteroid; the image was captured in 2005 by Franck Marchis using adaptive optics at the 10-m Keck telescope. Patroclus is $D \simeq 120$ km, and its companion Menoetius (father of Patroclus) is $D \simeq 110$ km. Their mutual orbit has $P_{\text{orb}} = 4.3$ days at a separation of 640 km (F. Marchis/UC Berkeley). Asteroid 2001 SN263 (right) is the first known NEO triple-system. It was imaged at the Arecibo radio observatory by Michael Nolan in Feb. 2008, as seen in this delay-Doppler image. Initial data reduction reveals the primary asteroid to be $\sim 2$ km in diameter, the larger moon $\sim 1$ km, and the smallest about 0.3 km (M.C. Nolan, Arecibo Observatory).

which is already spinning with a period of only 12 min, is expected to double in a few 100,000 years, perhaps flinging it apart.

The spin-up of asteroids can have dramatic consequences (Scheeres 2007) and is likely to be a mechanism for global reshaping and resurfacing and satellite formation (Walsh et al. 2008) and binary evolution (Cuk 2007), as discussed further below. A detailed review of Yark and YORP is found in Bottke et al. (2006b).

1.3.2. Groups and gaps. Inner solar system resonances with Jupiter and Saturn create not only gaps but also groups within sheltered regions of dynamical space, as seen in Figure 8. One group is the Hilda asteroids, which librate at the 3:2 mean motion resonance near 4.0 AU, forming a subtle triangular distribution in space (see Figure 2). Another group is found at the 1:1 resonance at 5.2 AU—leading and trailing Jupiter by 60° at its orbital distance from the Sun. These are the Trojan asteroids, which occupy halo orbits (in the Jupiter-fixed frame) about either of the two stable minima (the leading $L_4$ and trailing $L_5$ Lagrangian points) of the Jacobi energy integral in the reduced 3-body problem. Are Hildas and Trojans asteroids? The one Trojan asteroid whose density has been measured, 617 Patroclus (Marchis et al. 2006; Figure 7) is cometary, with $\rho \sim 0.8$ g/cm$^3$. For comparison, the density determined for the 1–2-km diameter Jupiter family comet Shoemaker-Levy 9 was about 0.6 g/cm$^3$ (Asphaug & Benz 1994, 1996), and the Deep Impact mission target 9P/Temple 1 appears similar (Richardson et al. 2007).

1.3.3. Families. Asteroid families are clusters in dynamical space (Figure 8) that are indicative of a common origin during impact disruption (Hirayama 1918). They are distinct from groups in

---

Figure 7

Asteroid 617 Patroclus (left) is the first known binary Trojan asteroid; the image was captured in 2005 by Franck Marchis using adaptive optics at the 10-m Keck telescope. Patroclus is $D \simeq 120$ km, and its companion Menoetius (father of Patroclus) is $D \simeq 110$ km. Their mutual orbit has $P_{\text{orb}} = 4.3$ days at a separation of 640 km (F. Marchis/UC Berkeley). Asteroid 2001 SN263 (right) is the first known NEO triple-system. It was imaged at the Arecibo radio observatory by Michael Nolan in Feb. 2008, as seen in this delay-Doppler image. Initial data reduction reveals the primary asteroid to be $\sim 2$ km in diameter, the larger moon $\sim 1$ km, and the smallest about 0.3 km (M.C. Nolan, Arecibo Observatory).

The spin-up of asteroids can have dramatic consequences (Scheeres 2007) and is likely to be a mechanism for global reshaping and resurfacing and satellite formation (Walsh et al. 2008) and binary evolution (Cuk 2007), as discussed further below. A detailed review of Yark and YORP is found in Bottke et al. (2006b).

1.3.2. Groups and gaps. Inner solar system resonances with Jupiter and Saturn create not only gaps but also groups within sheltered regions of dynamical space, as seen in Figure 8. One group is the Hilda asteroids, which librate at the 3:2 mean motion resonance near 4.0 AU, forming a subtle triangular distribution in space (see Figure 2). Another group is found at the 1:1 resonance at 5.2 AU—leading and trailing Jupiter by 60° at its orbital distance from the Sun. These are the Trojan asteroids, which occupy halo orbits (in the Jupiter-fixed frame) about either of the two stable minima (the leading $L_4$ and trailing $L_5$ Lagrangian points) of the Jacobi energy integral in the reduced 3-body problem. Are Hildas and Trojans asteroids? The one Trojan asteroid whose density has been measured, 617 Patroclus (Marchis et al. 2006; Figure 7) is cometary, with $\rho \sim 0.8$ g/cm$^3$. For comparison, the density determined for the 1–2-km diameter Jupiter family comet Shoemaker-Levy 9 was about 0.6 g/cm$^3$ (Asphaug & Benz 1994, 1996), and the Deep Impact mission target 9P/Temple 1 appears similar (Richardson et al. 2007).

1.3.3. Families. Asteroid families are clusters in dynamical space (Figure 8) that are indicative of a common origin during impact disruption (Hirayama 1918). They are distinct from groups in

---

Family: asteroids occupying a compact region of dynamical space, indicating a common origin from an impact disruption event

---

The leading ones at the L4 are sometimes called the Greeks, and are named after Greek heroes in the Trojan war, although Achilles’s dear friend Patroclus somehow made it into the L5 Trojan camp.
Asteroid proper elements are orbital elements in which solar precession and planetary perturbation effects have been removed; unlike standard (osculating) orbital elements, which vary over thousands of years, proper elements remain approximately constant over millions of years, bringing youthful asteroid dynamical clusters into high focus. (a) A slice through the semimajor axis; the Kirkwood gaps (see also Figure 6) show up in the main belt at the primary mean motion resonances with Jupiter. (b) The clusters of asteroids that show up most vividly in proper $e - i$ space are the asteroid families that result from catastrophic collisions; the most dense clusters are generally the youngest. Asteroids in a given asteroid family are, however, out of phase and well-mixed in Cartesian space. Image from Petr Scheirich.

being related to a source (parent asteroid) rather than a sink (chaotic boundary domain) or trap (stable domain). Some of the larger asteroid families, notably Koronis, are boxed in by resonances. Using hierarchical clustering methods (Zappala et al. 1995) applied to proper elements, hundreds of asteroid families have been discovered, and about one-third of all asteroids have been determined to be members of a known dynamical family. Because the lifetimes of most families are considerably younger than the age of the solar system, most asteroids have at one time been part of families long since dispersed.

1.3.4. Binaries. Almost 200 binary minor planets have been discovered, primarily through lightcurve analysis, and almost one-sixth of NEAs are binary systems (see Figure 7). Binaries may form by tidal passage near a planet, akin to what happened to comet Shoemaker-Levy 9 (Asphaug & Benz 1996, Bottke & Melosh 1996), or they may form by a catastrophic disruption event (Durda et al. 2004). Capture by dynamical friction and 3-body encounters (Goldreich et al. 2002) is possible in the early outer solar system but unlikely for asteroids. A promising scenario for binary formation among NEAs is fission in the aftermath of YORP-induced rotation (Walsh et al. 2008), based on the fact (Pravec & Harris 2007) that most known binaries would be close to the spin barrier discussed above if combined into a single body. Once a binary is formed, YORP continues to torque both members of the system, and rotational-orbital coupling may drive the binary to greater semimajor axis (e.g., Ćuk 2007).

Understanding binary formation and evolution is undoubtedly an important component to understanding planetesimal accretion, family origins, and asteroid shape, surface, and structural evolution. A dedicated mission to a binary minor planet would have very high scientific merit.
Rubble pile: a geologic mass whose chief binding force is gravitation, but whose central pressure is far lower than the strength of rock. Dynamically, an asteroid or comet that cannot hold onto its own pieces if it is spun up by gentle stresses such as tides or YORP.

2. STRANGE NEW WORLDS

Eros is the largest of the Amor dynamical group of NEAs and is the first small body ever orbited by a spacecraft (Veverka et al. 2000). 25143 Itokawa was visited by the Hayabusa mission in late 2005 (Fujiwara et al. 2006), the second asteroid rendezvous (Figure 9). Orbiting was only undertaken at Itokawa in discrete arcs, where one applies tiny thrusts to hold a desired position or trajectory—in this case trailing a bit behind the terminator, where asteroid gravity balances the solar wind that blows the spacecraft downstream. Navigating the smallest asteroids is a lot like sailing.

2.1. Eros

The first look at Eros revealed an oddly shaped rock of monolithic structure (Veverka et al. 2000) rotating every 5.26 h, cracked and faulted by impacts (Prockter et al. 2002), a “shatter pile.” However, others looking at the same data (Asphaug et al. 2002) saw a modestly cohesive rubble pile of talus and dirt, heaped by impacts into an odd shape, the faults being fissures in low-gravity dirt—a true rubble pile.

The data for Eros consist of high-resolution images, compositional characterization (Trombka et al. 2000), a shape model (Thomas et al. 2000, Zuber et al. 2000), a bulk density (2.7 g/cm$^3$; Yeomans et al. 2000), and a well-characterized dynamical state (Miller et al. 2002). A reasonable compositional match is found in ordinary chondrites, common meteorites that have similar spectral and albedo characteristics, but a higher bulk density $\sim$3.4–3.7 g/cm$^3$. If made of this material, Eros has a porosity of $\sim$25%, the same as for talus piles and sand beds on Earth, but also consistent with a highly faulted structure. Arguing for structure on the basis of density or composition is, for Eros, inconclusive.

A shattered monolith structure for Eros is argued on the basis of irregular shape—only a body with structural integrity can support a ridged topography—and the existence of faults that seem to require bedrock geology. As to the first argument—which has been applied to comet Halley and other irregular bodies—gravity is also irregular, owing to the peanut-like shape and fast rotation. Eros is actually rather flat: local slopes at 100 m baseline (Zuber et al. 2000) are generally shallower than $\sim$20°, relative to the local geopotential, except for inside crater rims that are at the angle of repose (Figure 10). Eros has the shape one expects for a rubble pile.
Figure 10
Slopes of asteroid 433 Eros taken at 100 m baseline, from the NEAR laser altimeter experiment (Zuber et al. 2000; figure reproduced from Asphaug et al. 2002). The shape model for Eros is shaded in degrees of slope between the surface normal and the vector of gravitational acceleration in the rotating frame of reference. The crater rims and a few other areas have local slopes of 30°–40°, whereas noncratered areas are relatively “flat,” like a landscape in lunar regolith.

As to the argument that faults require bedrock, consider the physics of the ∼10 to 100-m-wide scarps on Eros. They are supported in the walls of long, linear fractures, some extending for kilometers, mostly running in parallel (Prockter et al. 2002). Similar structures are found on other asteroids, including Ida, Gaspra, and Phobos. One idea (e.g., Fujiwara & Asada 1983, Asphaug et al. 1996) is that these fractures are the result of impact stresses focusing in the finite body of the asteroid and interacting with the free surface. Other ideas include thermal stresses (Dombard & Freed 2002) and body stresses induced by changes in spin.

Faulting can occur in a granular matrix. Any visitor to a beach knows that sand can fracture when it is cohesive relative to the applied stress, and therefore micro-cohesions support scarps in microgravity. Cohesion measured for lunar regolith (∼10⁴–10⁵ dyn cm⁻²; Mitchell et al. 1972) exceeds the gravitational overburden in the upper ∼10–100 m on Eros, so that its regolith may support a fractured exterior, even though the same material brought back to Earth would behave as an incohesive pile. This hypothesis, that Eros is a fractured rubble pile, makes sense in light of the thousands of fractures mapped on Eros (Buczkowski et al. 2008), whose formation in a solid bedrock seems impossible to achieve without jumbling the structure of the asteroid, unless the fracture stress is minuscule. If so, then impacts or other stresses create the fault patterns by opening up cracks in the upper tens of meters of dirt, not in solid rock. Continuous deformation throughout the interior (bending or torsion) would be expressed as continuous global-scale fault structures, whereas impact reverberation might create en echelon fissures.
2.2. Itokawa

We speculate about the internal structure of Eros even after a one-year rendezvous. Smaller asteroids appear even stranger by degrees. When the Japanese Hayabusa spacecraft (Fujiwara et al. 2006) arrived at 25143 Itokawa in late 2005, the images it acquired (Figures 11) defied all expectations.

Only 1/200,000 the mass of Eros, Itokawa was expected to be a monolith, or perhaps a couple of massifs resting together with a sprinkling of coarse regolith. Surface gravity is smaller than even the imperceptible jostling experienced by spacecraft in low-Earth orbit; any loose regolith was expected to have floated free, ejected by impacts and other processes. Instead, what was discovered was a coarse pile of rocks on a landscape almost devoid of recognizable craters, with global-scale flat gravel expanses ("seas"). It appears to be a rubble pile (Fujiwara et al. 2006), but what is inside remains conjecture.

2.3. Classes of Asteroids

Asteroids are divided into taxonomic groups and types on the basis of their spectroscopic and photometric properties. (New classes and sub-classes of asteroids have been developed on the basis of combined visible and infrared observations; see Bus and Binzel 2002. This review sticks to the traditional Tholen taxonomy; see Burbine et al. 2002.) Near-Earth space and the inner main belt are dominated by S-types like Eros and Itokawa.

But only ~15–20% of all known asteroids are S-types. More common throughout the main belt (approximately 75% of known asteroids) are the C-type asteroids that dominate the middle and outer main belt. The only C-type asteroid imaged by spacecraft is Mathilde (Figure 3 and Figure 12), observed during the 1997 NEAR flyby; the Martian satellites Phobos and Deimos are also loosely in this group.
Two radically distinct major asteroids illustrate the diversity of the main belt: one a primitive and extremely porous rocky body, and the other a spinning equilibrium figure of iron. (left) 453 Mathilde ($D = 53$ km) was the first flyby target of the NEAR mission; it has a half-dozen gargantuan craters and a density of $\sim 1.3$ g cm$^{-3}$ (see text). It is also one the most slowly rotating bodies in the solar system, $P_{\text{rot}} = 17.4$ days (NASA/APL). (right) 216 Kleopatra, shown in a shape model reconstructed from ground-based radar observations at Arecibo (Ostro et al. 2000), is a metallic M-class object 220 km long, with a bulk density of about 6 g/cm$^3$ if one fits an equilibrium shape to its rapid 5.4 h rotation. The radar-determined surface porosity is about 50%, comparable to the porosity of the upper meters of the lunar regolith (Ostro/JPL).

Figure 12

Generally speaking, as one goes from the inner solar system to the outer solar system, one goes from S-type to C-type domains, possibly on account of the more rapid timescale of planetesimal accumulation closer to the Sun (see Section 3).

The complete taxonomy of asteroids includes numerous sub-groupings. C-, P- and D-type asteroids are as dark as charcoal (visual albedo $p_v \sim 0.05$) and reddish; they are presumably made of the same materials as the most primitive meteorites, the carbonaceous chondrites, which include complex organic molecules in addition to silicate minerals and reduced iron and other metals. D-types are particularly red at long infrared wavelengths and may be rich in organic compounds. S-type asteroids are several times brighter than C-type asteroids (visual albedo $p_v \sim 0.15$) and have distinct silicate absorption bands; they are probably made of similar materials as those of the most common meteorites, the ordinary chondrites, which are moderately evolved but unmelted chondritic rocks. The M taxonomic class was originally conceived as consisting of metallic fragments of differentiated planetary cores, either blasted apart in some cataclysmic event or otherwise missing their mantle rock (see below). Metallic asteroids are expected to have rock-like rheology at cold temperatures, but there is no past or planned spacecraft visit to a metallic M type (e.g., Kleopatra in Figure 12), and we might not find out for decades.

M-type: a class of asteroid with moderate albedo and a flat, featureless spectrum at visible wavelengths; some of these are metallic parents of the iron meteorites; many are now known to be hydrated silicates of a very different origin

Space weathering: the process of surface reddening and darkening that occurs as minerals and metallic inclusions are exposed to the high energy bombardment of space

One advancement based on mid-infrared spectroscopy (Rivkin et al. 2000) is that the M-type asteroids larger than $\sim 65$ km are likely to be of hydrated silicate mineralogy, not metallic. Thus the largest metallic M-types, for instance 216 Kleopatra ($\sim 220 \times 90$ km; Figure 12) and 16 Psyche ($D \approx 250$ km), are anomalous and uncommon (though perhaps representing the bulk of the mass of the M types). Asteroid 21 Lutetia, the large ($D \approx 100$ km) M-class flyby target of the Rosetta mission to comet 67P/Churyumov-Gerisamenko is probably of non-metallic composition.

Space weathering of asteroid surfaces (see Sasaki et al. 2001 and references therein) can cause all asteroids to redden and darken, or otherwise change their spectroscopic characteristics. What is
Absolute magnitude: $H$

$H$ is what an asteroid’s apparent magnitude would be at zero phase angle at 1 AU from the Sun and 1 AU from Earth, extrapolated from observations. A proxy for diameter

Equilibrium figure:
the shape of a rotating planetary body whose pressure gradients balance the gravitational and centrifugal forces (e.g., a liquid)

learned from studying the upper few microns of surface layering needs to be taken alongside what has been learned from spacecraft observation, from meteorites, and from future in situ asteroid studies.

2.4. Photometric Characterization

By measuring an asteroid’s absolute magnitude $H$ (its visual magnitude at 1 AU from the Sun and 1 AU from Earth, at zero phase), one can estimate asteroid diameter $D$ according to

$$D \approx 1329 \text{ km} \times 10^{-H/5} p_v^{-1/2},$$

where $p_v$ is the visual albedo. For the average NEA albedo $p_v \approx 0.14$, asteroid diameters $D \approx 6, 2, 1,$ and $1/3$ km correspond to $H \approx 14, 16, 18,$ and $20$. But $p_v$ varies by a factor of $\sim 3$ between S- and C-types, making C-types $\sim 50\%$ larger than S-types of the same magnitude.

Asteroid rotation rates and shapes are derived from brightness variations. Sometimes these light curves are simply periodic, with each half-rotation going from bright (face-on) to dim (end-on). Simple models of rotating ellipsoids can be fit to many asteroid light curves by specifying the spin pole, the principal axes’ dimensions, the albedo, and the phase function. Nonellipsoidal asteroids that are rapid rotators are sometimes fit by some other equilibrium figure, such as a Roche binary (see, for example, Figure 12).

Many asteroid light curves cannot be explained by a single rigid body, leading to the understanding (Weidenschilling et al. 1989) that asteroids have satellites. From the detailed study of light curves, Pravec et al. (2006) estimated that $\sim 15\%$ of near-Earth asteroids with $D > 0.3$ km are binary systems with the diameter ratio of the pair $> 0.18$. The percentage of binaries is particularly high among NEAs smaller than 2 km and decreases at large sizes. This observation confirmed the earlier study by Margot et al. (2002) of NEA binaries based upon radar observations.

The orbital period $P$ is related to the combined mass $M$ of a binary asteroid system by $P^2 = 4 \pi^2 a^3 / GM$, where $G$ is the gravitational constant. If the system is resolved so that the semimajor axis $a$ is known, then $M$ is deduced from $P$ (the light curve period). The individual masses of the components, and then their densities, are further derived by estimates of relative brightness (relating to relative size).

A fundamental asteroid data set is the rotation period $P_{rot}$ versus $D$, derived from light curves and plotted in Figure 13 (Pravec et al. 2002). For asteroids $D \lesssim 200$ m, rotation rate attains a maximum, a “spin barrier” of $P_{rot} \approx 2$ h, which is—probably not coincidentally—the fastest rotation period a sphere of density $\sim 2$ g/cm$^3$ can rotate without throwing material off its equator. The spin barrier is further shown by Pravec et al. (2007) to move to longer periods for asteroids with greater light curve amplitude (oblateness), as would be expected of a sphere spinning itself out into an ellipsoid.

Before we conclude that asteroids $D \gtrsim 200$ m are rubble piles, and those smaller are monolithic, we must note that internal friction (Holsapple 2007) could hold fast-rotating asteroids together even in the absence of cohesion. As for larger asteroids that cluster near the spin barrier, the mechanism by which they would lose mass during spin-up is not clear (see Walsh et al. 2008). It is evident from the study of binary rotation rates (Pravec & Harris 2007) that the combined angular momentum of most asteroid pairs lies at or near the spin barrier. A genetic mechanism for binary formation may be that they spin up (by YORP) beyond this threshold and suffer a global landslide that sheds a moon.
2.5. Spectroscopy and Thermal Observations

Spectroscopy from Earth is usually disk integrated, taking in a hemisphere at once. It can be rotationally resolved—recorded as the asteroid spins, documenting global-scale heterogeneity. From visible and near-infrared spectroscopy one derives the taxonomic class and a wealth of compositional information. From mid- to thermal-infrared studies, one obtains vital information regarding thermal properties, important to understanding Yarkovsky and YORP evolution.

Combined thermal and visible observations solve independently for albedo, giving a constraint on size and (via the light curve) shape. Spacecraft missions provide essential benchmarks in this regard. Itokawa is a small S-type asteroid with absolute magnitude $H \sim 19$. Müller et al. (2007) reported pre-encounter ground-based thermal observations at 10 $\mu$m, leading to a shape model of $320 \times 270 \times 230$ m ($\pm 10\%$); this was in excellent agreement with the shape measured by Hayabusa of $335 \times 294 \times 209$ m (Fujiwara et al. 2006).

2.6. Radar

The 305-m diameter Arecibo dish—larger than some of the asteroids it images—is the world’s most powerful radio transmitter, capable of sending $\sim 0.5$ MW pulses. It is also the world’s most sensitive radio receiver, acquiring reflected energy $< 10^{-27}$ watt at high signal-to-noise. Arecibo Observatory, together with the 70 m steerable dish at Goldstone Observatory, has been utilized...
with great success by the late asteroid radar pioneer Steve Ostro and his colleagues to provide the most detailed images and dynamical information known about NEOs as well as important characterization of main-belt asteroids and Earth-approaching comets. The topic is reviewed by Ostro et al. (2002).

Asteroid radar operates by sending out a narrow beam of microwave energy toward a target (3.5 cm at Goldstone, 13 cm at Arecibo), and by examining the echo in comparison to the transmitted signal. A circularly polarized signal enables studies of surface roughness and albedo, which in turn lead to an understanding of the porosity and composition of the upper centimeters.

Radar is subject to two-way $1/r^4$ signal attenuation, and thus high-resolution images generally require closest approaches $\lesssim 0.01$ AU, although shape models and spin poles can be obtained at lower signal-to-noise ratio (SNR). For the main belt, radar-derived shape models rival adaptive-optics imaging, but the most significant main-belt radar data set is the detection of their surface physical characteristics. Magri et al. (2007) report that M asteroids come in both metal-rich and metal-poor varieties, as indicated above, and that C- and S-class MBAs have indistinguishable radar albedo distributions. Benner (2008) correlates radar roughness with composition, opening up new avenues in science and showing how radar detection is a valuable precursor to landed missions and sample returns.

In addition to producing stunning images and other physical characterizations, radar provides extraordinarily precise astrometry, allowing for highly refined dynamics, both orbital (about the sun) and rotational (the asteroid system itself). Chesley et al. (2003) describe its utility in asteroid dynamical studies (in this case the first direct determination of the Yarkovsky effect), and Giorgini et al. (2008) show how radar astrometry is an essential tool in retiring the risk of menacing objects like Apophis. Scheeres et al. (1996) were the first to use radar-derived shape models and spin states as initial conditions for studying particle dynamics about an asteroid, and Scheeres et al. (2006) obtain a detailed understanding of the dynamical state of the 1999 KW4 system (Figure 14).

### 2.7. Dynamical Constraints

Large asteroids have had their masses directly measured from their perturbations upon Mars and on each other (Williams 1984, Michalak 2000). Krasinsky et al. (2002) derived the total mass of the asteroid belt by analyzing the motions of the major planets, processing high-precision ranging information relative to the Viking-1, Viking-2, and Pathfinder landers over a 21-year period. They modeled the 300 largest asteroids and the major planets directly, and the residual gives the “hidden mass” of the belt. According to their studies, the total main-belt mass is $\sim 1.8 \times 10^{-9} M_\odot$, where $M_\odot$ is the mass of the sun, thus $\sim 3.6 \times 10^{21}$ kg is the total mass of asteroids according to this study. That is 400% the mass of Ceres, $\sim 0.6\%$ the mass of Mars, and $\sim 5\%$ the mass of the Moon.

Asteroid masses are also determined through the study of multiple systems, via Kepler’s laws, and through studies of rotational equilibrium. The primary density of 1999 KW4 (Figure 14) is $\sim 2$ g cm$^{-3}$; the satellite density is probably somewhat greater (Ostro et al. 2006). With $P_{rot} = 2.76$ h, the primary is rotating close to the speed limit where debris goes into orbit (see Scheeres et al. 2006). Slope maps of the primary including rotation show it to be near the angle of repose at mid-latitudes; it may be a celestial debris flow with material migrating to the equator. Fine particles that are shed from the equator may be swept out by the solar wind; larger rocks might accumulate back onto the asteroid or onto the satellite, their fate depending on whether they escape rock-by-rock or as a landslide.
Two of the many asteroids imaged by the radar telescopes at Arecibo and Goldstone; for a complete list see http://echo.jpl.nasa.gov. (a) 1999 JM8 is a $D \approx 2.5$-km S-type, the largest potentially hazardous asteroid (PHA) to be studied in this level of detail (Benner et al. 2002). These are Doppler-delay images acquired in 1999, shortly after the object’s discovery, on the dates labeled (Benner/JPL). (b) 1999 KW4 is a binary system (Ostro et al. 2006) that will come to within 13.5 lunar distances of Earth on May 25, 2019. This is another potentially hazardous S-type whose high inclination ($\sim 40^\circ$) and large eccentricity ($\sim 0.7$) indicate that it has undergone a near-Earth scattering encounter—possibly the event that created the binary by tidal disruption. It will come within 6 lunar distances of Earth in 2036, close enough to transform its dynamical configuration. This is a shape model fitted to the radar observations, with primary diameter $D_A \approx 1.5$ km, secondary diameter $D_B \approx 0.5$ km, and separation $a \approx 2.5$ km (Ostro/JPL).
3. ORIGINS

There all the barrel-hoops are knit,
There all the serpent-tails are bit,
There all the gyres converge in one,
There all the planets drop in the Sun.

William Butler Yeats, “Supernatural Songs”

Asteroid origin is ceaseless, as most asteroids are born in the process of catastrophic disruption. Any main-belt asteroid smaller than a few tens of km is unlikely to have survived intact throughout solar system history. Asteroid evolution is also ongoing: Most small asteroids have been drastically transformed in shape and structure over a few tens of millions of years by subcatastrophic collisions and cratering. Small asteroids are also prone to dynamical perturbations of various kinds, so their present orbits may be quite different from where they originated. Their surface textures and colors are also readily modified on short timescales.

But meteorites, which sample the asteroids, are largely primordial. It is therefore difficult to say just what is meant by “asteroid origin,” since they are petrologically the most ancient, and dynamically the newest, of planetary bodies. Because the dynamical and collisional lifetimes of small asteroids are much shorter than the age of the solar system, we can distinguish dynamical origins from petrological origins, and begin with the former.

3.1. Ages of Families

Most MBAs smaller than a few tens of km are catastrophic disruption remnants (Farinella et al. 1982). The ejection of sizable fragments upon impact, followed by the long-term dynamical forcing by planetary encounters, resonances, and the Yarkovsky effect, causes families of asteroids to form and disperse. The snapshot of the present epoch seen in Figure 8 will look similar in ~10 Ma, except that most of the smaller families will be gone, replaced by new ones.

Researchers date the time of formation of asteroid families by modeling their dynamics backwards until family members converge. A couple of smoking guns have proven quite young, and their debris have been associated with the lunar and terrestrial impact record. The Karin family (proper $a = 2.87$ AU, $e = 0.044$, $i = 2.1$; itself a subcluster of the Koronis family) and the Veritas family (proper $a = 3.17$ AU, $e = 0.065$, $i = 9.3$) formed only ~5.8 Ma and ~8 Ma ago, respectively (Nesvorný et al. 2002). The Datura family (Nesvorný et al. 2006) is dated to only 450,000 years ago.

Some of these very young families include binary asteroids, suggesting that binaries can be formed during catastrophic collisions (Durda et al. 2004), either through ejection of bound pairs or ejection of material into orbit about the target. But not necessarily; the creation of new satellites around ~1-km asteroids may take as little as ~1 Ma if YORP spins them up as rapidly as postulated.

The Karin family members do not align perfectly at ~5.8 Ma before present, when projected back in dynamical time. Allowing for Yarkovsky drift, Nesvorný & Bottke (2004) obtain an excellent convergence, but only if the fragment asteroids are of low thermal inertia—that is, regolith-covered shortly after the catastrophic breakup event. If true, this would give insight into the process of disruption.

The Baptistina family of asteroids has been shown through dynamical integrations (Bottke et al. 2007) to have formed during a collision ~160 Ma involving parent asteroids modeled as 60-km and 170-km diameter. One large fragment from this breakup is thought to have struck the Moon, forming the rayed crater Tycho 108 Ma ago. A more infamous outcome of these simulations is that
3.2. Planetesimals to Planets

Asteroids represent the halfway point between the solar system’s turbulent beginnings and the quiescent 4 Ga that have supported life on Earth.

The first stage of planetary accretion is among the most complex studies in astrophysics. As they accumulate, planetesimals are entrained within a disk that undergoes violent shocks and propagates gravitational waves and eddies. Magneto-rotational instabilities might lead to high turbulent viscosities, which lead to radial transport and vertical mixing and viscous spreading. Solid particles settle to the mid-plane, increasing the density so that planetesimals might eventually coagulate. Electric discharge and impact heating take place sporadically. Outside this mid-plane the young sun blasts the gas and sweeps away small material. Drag against the gas disk forces meter-sized boulders to spiral in from the planet-forming region.

The chemical environment, too, is grossly out of equilibrium. The disk experiences a wide range of temperatures and pressures and oxidation states, with sharp gradients in time and space. Where the disk is optically thick, it can remain hot for thousands of years; where it is thin, it can cool in days or even minutes. Thermodynamic energy is available from solar heating, shock heating (by impacting globules striking the disk, by disk planetesimals colliding with one another, and by shocks in the gas), compression heating (adiabatic work), and radionuclide decay. This energy is transported radiatively and convectively.

One of the most baffling results from any recent space mission is NASA’s Stardust sample return from periodic comet 81P/Wild 2 (Brownlee et al. 2006; see Figure 3), which includes an abundance of refractory silicates, metal sulfides, and refractory oxides. These small grains, captured in aerogel during a flyby through the coma, can have formed only in the terrestrial (inner) part of the disk; how did they make it to the ice-rich region where comets form? It is a revolutionary mission result, telling us that the solar system was exchanging matter across tens of AU during the early stages of primary accretion.

3.2.1. A standard model. As terrestrial planet formation progresses the pace of events drops off, so there appear to be stages that are logarithmic in time. Primary accretion, described further below, begins with the Sun’s formation within a possibly dense cluster of young stars; it ends with the condensation of dust- to boulder-sized solids in a hot, turbulent, violently irradiated disk.

Primary accretion is surprisingly rapid: solids collapse down onto the mid-plane of the nebula and coalesce into dense swarms of meter- to kilometer-sized planetesimals in as little as a few tens of thousands of years.

Over the next ~1 Ma, these small solids grow into planetesimals resembling the most primitive asteroids. This is also the timescale of the decay of $^{26}$Al $\rightarrow ^{26}$Mg, a radionuclide predating accretion with half-life $t_{1/2} = 7.2 \times 10^5$ yr. Global melting ensues if planetesimals grow large enough and fast enough, so there should be a wide diversity of metamorphic and igneous grades among meteorites, in agreement with observation. After this epoch the internal heat sources shut down, asteroids being too small to retain the heat produced by longer-lived radionuclides.

Over the next ~10 Ma, the disk is quiescent and composed primarily of accreted solids. Gravitational instabilities early on cause large planetesimals to grow much more rapidly than small ones (Greenberg et al. 1978, Wetherill & Stewart 1989); competition for matter thereafter slows down the growth of larger bodies in comparison to small ones (Kokubo & Ida 1998).
Thus, runaway growth levels off into oligarchic growth, resulting in planetary embryos that are comparably sized and uniformly spaced and follow approximately circular orbits \((e, i \approx 0)\). They are perhaps Vesta to Moon- or Mars-sized, depending on the mass density of the disk.

Accretion is a lossy process, and the original disk mass is greater than the final terrestrial planetary mass by a factor of perhaps \(\sim 2 \pm 1\) that is removed by dynamical and gas drag and scattering (Figure 15). This winnowing is most pronounced among the small bodies that are most easily perturbed.

An epoch of large-scale impacts dominates the next 100 Ma, beginning at low velocity among these like-sized bodies and evolving toward higher-velocity collisions among different-sized bodies. Low velocity refers to \(v_{\infty}\) compared with the two-body escape velocity

\[
v_{esc} = \sqrt{2G(M_i + M_t)/(R_i + R_t)}. \tag{7}
\]

Here, \(M_i, M_t\) and \(R_i, R_t\) are the masses and radii of the impactor and target, and \(G\) is the gravitational constant. The impact speed at the moment of contact is the root square sum \(v_{imp} = \sqrt{v_{\infty}^2 + v_{esc}^2}\) and is at minimum the escape velocity. Because the population gets dynamically stirred up by the largest body, \(v_{\infty}\) is comparable to the escape velocity.

Low-velocity impacts transition to high-velocity impacts as close encounters gravitationally excite the population. Planet-sized bodies go astray, as is believed to have happened when a
Mars-sized body struck the Earth to form the Moon. In a series of papers that developed the modern theory, Wetherill (1990) showed that Mars-sized protoplanets would have roamed the main belt for the first 10–100 Ma. Mercury could have originated from beyond Mars (Wetherill 1994). Asteroids, then, are what’s left after roaming planets did their work (Chambers & Wetherill 2001).

To continue logarithmically, the next 1 Ga was an epoch where largely finished planets suffered the remainder of the planetesimal bombardment, with occasional impact storms triggered by the playing out of the final dynamical instabilities, as indicated by the late lunar cataclysm—the pronounced spike in the cratering record ∼3.9 Ga before present, around the time life originated on Earth. A final logarithmic step includes the placid times we enjoy today and the winding-down of the thermodynamical inventories of the solar system, followed by the death of the Sun ∼10 Ga after it all began.

3.2.2. Primary accretion. Direct knowledge of the earliest stage now exists from astronomical observations (e.g., Meyer et al. 2008). As the hot orbiting mixture of dust and gas cools, larger particles condense, leading to lowered opacity and further cooling and coagulation. The review by Podosek & Cassen (1994) remains highly relevant. Particles orbiting with any inclination or eccentricity must plow through the disk; the resultant damping settles them to the midplane on a timescale of ∼100 years at 1 AU (Cuzzi & Weidenschilling 2006). What happens next in this central sheet is a great unknown, and depends on the effect of turbulence.

Dust grains coagulate via Brownian motion and chemical or electrical sticking mechanisms (Dominik et al. 2007). Brownian motion is an expression of modest turbulence, possibly set up by magneto-rotational instabilities in the plasma and the dusty gas. However, too great a turbulence disrupts agglomerates faster than they form. Benz (2000) and Leinhardt et al. (2000) studied collisions involving meter- to kilometer-scale aggregates at ∼1–10 m/s random velocities, and determined their disruption to be a bottleneck to further growth. A possible solution is that compactible aggregates damp the energy of collisions and resist subsequent disruption.

Not only must turbulence be low, but the gas must go away before the growing planetesimals spiral in. Once boulder-sized, they decouple and drag against the pressure-supported gas disk that orbits the Sun at a sub-Keplerian velocity

$$v_k = \sqrt{\frac{GM_\odot}{r}} = \left(1 - \frac{dP/dr}{2\rho g \Omega_k^2 r}\right) v_k,$$

where $v_k = \sqrt{\frac{GM_\odot}{r}}$ is the Keplerian velocity of the boulders, $dP/dr < 0$ is the drop of pressure $P$ with increasing heliocentric radius $r$, $\rho g$ is the gas density, and $\Omega_k = \sqrt{\frac{GM_\odot}{r^2}}$ is the Kepler frequency. Decoupled solids spiral towards the Sun at an estimated 1 AU per ∼10–1000 years, so there is not much time!

Multistage processes have been proposed to make primary accretion more efficient. The model by Cuzzi et al. (2001) capitalizes upon large-scale turbulence by having small particles coalesce in the disk eddies, analogous to how flotsam accumulates in a river. Thus the turbulence that would bash planetesimals apart collects them together. The clustering of solids into localized regions, either through random effects or through accumulation along stable zones, might lead to dense swarms that can then undergo gravitational coagulation.

The problem of accreting meter-scale planetesimals is far from solved. But we know it occurred rapidly because of the widespread melting of planetesimals caused by the decay of $^{26}$Al. Heat can only dissipate in a solid body by conduction or by volatile convection through pores and by radiation from the surface. A 10-km chondritic body easily melts if it acquires much faster than...
Achondritic: refers to an asteroid or meteorite of evolved or melted silicate composition.

\[ \tau_{1/2} = 0.72 \text{ Ma}, \]  
(as reviewed in Ghosh et al. 2006) or can undergo vigorous hydrothermal convection (e.g., Travis and Schubert 2005).

Timing is everything. So is location. Planetesimals forming closer to the Sun acquire a greater fraction of Al-bearing silicates than those forming where ices dominate and form more rapidly, and they are thus much more prone to melting. Large comets may also have melted interiors, despite the lower silicate abundance, owing to their low heat capacity, low thermal conductivity, and low melting temperature, provided they can win the race against \( \tau_{1/2} \) (as reviewed by Prialnik et al. 2008).

Melting during planetesimal accretion was widespread; there appear to be \( \sim 50 \) or more differentiated early planets whose cores are represented by meteorites, distinguished on the basis of bulk composition (Fe and N) plus trace metals. Each iron meteorite reservoir bears a unique chemical fingerprint; there are 14 classified groups plus hundreds of unclassified iron meteorites that belong to dozens of distinct parent bodies (Wood 1964). The possibility of multiple core-pockets of iron on a single parent body appears unlikely given the runaway nature of core formation, but it cannot be ruled out. Achondritic basalts, although not as abundant as irons, are just as diverse and directly indicate multiple diverse parent bodies, presumably among the same ones sampled by iron meteorites.

Why so few mantle and crustal rocks, and so many irons, among the meteorites? Burbine et al. (1996) reviewed the problem and proposed that mantle material in the main belt undergoes rapid breakdown in size whenever excavated from an asteroid, whereas the stronger iron relics survive. But unless chondritic rock is much stronger than mantle rock, the same argument should get rid of the chondrites as well, unless they were initially much more abundant. Or, chondrites could fragment with a steeper size distribution than basalts, leading to dominance at the small sizes pertaining to meteorites.

3.2.3. Chronology of differentiation and chondrule formation. Early solar system chronology is established through the study of short-lived radioisotopic nuclides and their decay products; these include Al-Mg (\( \tau_{1/2} = 0.72 \) Ma), Fe-Ni (\( \tau_{1/2} = 1.49 \) Ma), Mn-Cr (\( \tau_{1/2} = 3.7 \) Ma), Pb-Ag (\( \tau_{1/2} = 6.5 \) Ma), Hf-W (\( \tau_{1/2} = 9 \) Ma), and Sm-Nd (\( \tau_{1/2} = 103 \) Ma). The reference point for chronology is the solidification of the refractory Ca-Al inclusions (CAIs) that formed earlier (\( t_0 \sim 4.567.3 \) Ga) than any other known solid (Amelin et al. 2002) and are commonly found in primitive meteorites.

According to the thermal arguments, any silicate planetesimal larger than approximately 10–50 km would have melted and differentiated had it accreted earlier than a few million years after CAI formation. The preponderance of primitive rock in the meteorite collection might mean that accretion had not finished by this time, for otherwise all we would have are mafic and basaltic silicates and irons and core-mantle mixtures such as pallasites. This reasoning, and the very precise dating of chondrules, has pushed the chronology of so-called primitive bodies away from the starting point. The evolved bodies accreted first: Iron meteorites and the most ancient achondrites predate the origin of chondrules by a few million years (Kleine et al. 2005). Primitive meteorites like Allende and Orgueil do not represent the oldest bodies, but are latecomers that formed after the \(^{26}\)Al was spent.

Distinct chronologies for accretion point to distinct locations within the disk. Accretion is fastest inside of 1 AU and much slower further out, in proportion to the faster dynamical timescales and greater density of material. Bottke et al. (2006a) calculate how rapidly forming inner solar system asteroids are scattered by terrestrial planet formation to mix with the native chondrites of the main belt. Had they formed early on and closer in, they would have melted, accounting for the exotic diversity of main-belt asteroids and the presence of irons and basalts where accretion timescales are much longer than a few million years. The scattering of molten planetesimals is
applicable to the hypothesis of Asphaug et al. (2006) that gravitational and mechanical shears during impacts resulted in pressure unloading of melts and partial melts, leading to exotic petrogenesis, which is preserved in the unaccreted remnants of the solar system.

The origin of chondrules adds another layer to the mystery, in that these are melt droplets of some kind, quite possibly themselves antecedent to global melting of planetesimals. Chondrules are melted silicate spherules a few mm in size that are abundant in chondritic meteorites (reviewed by Scott 2007). Over half the bulk mass of chondritic meteorites consists of chondrules, so they represent a widespread epoch in planet formation that has been attributed to processes as diverse as lightning, impacts, nebular shocks, compaction heating, and volcanic eruptions. Chondrules cooled through their solidus at rates ranging from \( \sim 10 \) to \( \sim 1000 \) K/h—much slower than radiative cooling of a mm-sized droplet, which is tens of seconds. Chondrule cooling appears to require a hot background that disappears over a timescale of hours.

High-precision (\( \sim 0.1 \) Ma) timing of chondrule formation indicates that their formation ages postdate the formation of the earliest basalts and iron cores by \( \sim 2–3 \) Ma (Connelly et al. 2008). The data are consistent with episodes of chondrule formation spanning a few Ma (e.g., Kleine et al. 2005), contemporary with the transition from primary to secondary accretion, when sizable planetesimals were first forming. Although impact origin of chondrules is not currently in favor, we have a lot to learn, and large, late collisions deserve a closer look.

### 3.3. Large Collisions

In almost all simulations of late-stage planet formation, giant impacts are treated as “sticky ping pong balls” undergoing perfectly inelastic collisions when they hit, forming a larger equal-mass sphere that conserves linear momentum. This was proven untenable by Agnor et al. (1999), who tracked angular momentum during such a calculation and showed that perfectly inelastic collisions lead to planets with impossibly fast rotation.

Under perfect accretion, the acquisition of angular momentum is a 3D random walk that departs from the origin; many of the planets studied by Agnor et al. (1999) thus end up with \( P_{\text{rot}} \approx 1–2 \) h. Some of the modeled planets experience rotational kinetic energy \( \frac{1}{2} M R^2 \omega^2 \) exceeding the binding energy of a self-gravitating sphere \( 3/5 G M^2 / R \); equating these gives a fastest possible rotation of \( P_{\text{min}} = \sqrt{\pi / G \rho} \), or 1.2 h for a planet of density 3 g cm\(^{-3}\). But rapid rotators deform into spheroids and become unstable at rotation periods closer to \( \sim 2 \) h.

Unrealistically fast rotations obtained in the simulations are the result of perfect sticking for impacts faster than \( v_{\text{esc}} \), or at grazing incidence. The efficiency of giant impact accretion was explored by Agnor & Asphaug (2004a), who used smooth particle hydrodynamics (SPH) to model a wide array of giant impacts, at varying relative velocity, and with varying impactor-to-target mass ratio (see Figure 16). These simulations used the same method that had been applied to giant impact scenarios for the Moon’s formation (Canup & Asphaug 2001), beginning with differentiated planets of Earth-like bulk composition (70 wt\% rock, 30 wt\% iron).

For velocities typical of this epoch of planet formation, approximately one-third to one-half of giant impacts are hit-and-run collisions, with the impactor rebounding and contributing little mass to the target (or in most cases, removing some of it). This is easily understood geometrically: the most common impact angle is 45°; and, for similar-sized bodies, this is an angle at which most of the colliding masses do not intersect but miss one another. Planets thus grow selectively, accreting most of their matter by low-velocity or head-on collisions and not during high-velocity or grazing events, as can be seen in Figure 17, which plots accretion efficiency. Hit-and-run outcomes cluster along the line of 0 accretion efficiency and are the most common group of outcomes. Thus, the fate of the unaccreted impactor is of considerable importance to asteroid and meteorite origins.
Hit-and-run impacts are common when planetary bodies of similar size collide at accretionary velocities (Agnor & Asphaug 2004a). Typical collisions are shown here involving differentiated planetary embryos with rock mantles (blue) and iron cores (red) in a 70–30 wt% ratio. Target mass $M$ is the mass of Mars; impactor mass is ($\text{top}$) $m = M/2$ and ($\text{bottom}$) $m = M/10$. Impact velocities are typical of the late stage, with $v_{\text{imp}} = 1.5 v_{\text{esc}}$ (top) and $v_{\text{imp}} = 2 v_{\text{esc}}$ (bottom). Impact angle is 30° from head-on in both cases. These are SPH simulations using the Tillotson equation of state. Collisions are shown before, during, and 3 h after the impact, in side view; particles are overplotted. Mantle is lost (iron fraction-enriched) from impactor and target in hit-and-run collisions. In ($f$) a chain of iron-enriched bodies derives from the impactor, a possible explanation for iron meteorites with vastly different cooling rates coming from common parent reservoirs. The impactor in ($c$) has lost over half its mantle and invokes a possible scenario for the origin of Mercury. Figure from Asphaug et al. (2006).

The impactor often sails on, severely transformed by the mechanical shears, gravitational torques, and tides (Figure 16). In some cases it is shredded into a chain of bodies, with those toward the center of the chain being iron-rich, and the others iron-poor. The prevalence of hit-and-run collisions makes it a late-stage pathway for the origin of exotic igneous asteroids, for volatile flux and iron–silicate intermingling, and for the bulk removal of planetary mantles and the stripping of iron cores.

Every terrestrial planet is the aftermath of giant collisions, and given the above, one might expect significant compositional diversity among terrestrial planets of the sort that one sees between the Earth and Moon. Venus and Earth are compositionally similar, whereas Mercury appears to have less than half the mantle rock of similar-sized Mars, and Vesta and Ceres (Figure 18) vary by almost a factor of 2 in density. There is clearly a trend toward greater diversity as one looks to the smaller terrestrial planets, something that can be understood by the fact that large planets are great homogenizers and were never ripped asunder the way that small planets were.

Collisional accretion is biased to favor the accumulation of iron cores at the expense of mantle rock, because impacts expend most of their energy in the mantles and crusts of colliding planets.
Accretion efficiency. Agnor & Asphaug (2004a) simulated giant impacts between differentiated terrestrial planets (see Figure 15). This plot includes calculations presented by Agnor & Asphaug (2004b). The velocity at infinity $v_\infty$ is the random velocity; the impact velocity is $\sqrt{v_\infty^2 + v_{esc}^2}$. According to dynamical integrations of late-stage accretion (Agnor et al. 1999), most giant impacts have Safronov number $\theta < 1$ ($v_\infty > \sqrt{2} v_{esc}$), in which case the accumulation of mass is inefficient. Impact angles are $0^\circ$ (dark blue), $30^\circ$ (light blue), $45^\circ$ (red), and $60^\circ$ (orange). Target to impactor mass ratio is 1:1 (circles), 2:1 (squares), and 10:1 (triangle). Accretion efficiency $\xi$ is the mass of the largest postimpact body ($M_1$) minus the mass of the largest preimpact body ($M_t$), compared to the total mass accretable ($M_i$). In the case of perfect accretion $\xi = \frac{M_1 - M_t}{M_i} = 1$; this occurs for random velocities close to zero. The Moon-forming scenario favored by Canup & Asphaug (2001) involves low velocity $v_\infty/v_{esc} \lesssim 0.1$ and plots close to the red triangle in the upper left. In the limit of no collision, or a perfectly elastic collision, or an impactor adding as much mass as it removes, $M_1 = M_t$ and $\xi \approx 0$. Erosion ($\xi < 0$; $M_1 < M_t$) plots below the line; catastrophic disruption (where $M_t = \frac{M_i}{2}$) requires events far to the right of this plot. The clustering of model outcomes at $\xi \approx 0$ represents the preponderance of hit-and-run collisions where the impactor bounces off largely intact (Asphaug et al. 2006).

and because exterior layers are of lower binding energy than cores. Thus, the most energetic collisions can remove much of a planet’s mantle, either by a direct hit (Benz et al. 1988) or by hit-and-run akin to Figure 16a–c. Removing a mantle by a direct hit requires very high collisional velocity, far to the right of what is plotted in Figure 17, and far outside the mid-range of what is expected (Agnor et al. 1999), whereas hit-and-run applies when $v_\infty$ is in the mid-range.

The overall trend in a collisional accretionary environment is the loss of atmosphere, ocean, crust, and mantle, the preferential accretion of dense materials into growing planets, the shedding-off of mantles, and the occasional disruption of single planets into multiples. This leads to a primary physical and chemical bias, a dichotomy among the accreted and the unaccreted. If finished planets are the loaves of bread, asteroids are the scraps on the floor of the bakery.
Ceres and Vesta, the two largest asteroids, to scale, as imaged by Hubble Space Telescope (NASA). These are among the highest-resolution images that exist for either until the Dawn mission arrives at Vesta in 2011 and at Ceres in 2015 (Russell et al. 2004). (Left) Ceres, $D \approx 900$ km, imaged in 2004 (HST ACS/HRC). (Right) Vesta, $D \approx 530$ km, imaged in 2007 (HST WFPC2). The figure of Ceres is consistent with a differentiated spheroid of rock and ice in rotational equilibrium (Thomas et al. 2005). Vesta is missing much of its southern hemisphere, the possible source of the V-class asteroids (Binzel & Xu 1993, Asphaug 1997).

3.4. Asteroids and Planets

Planets still roam the main belt; the largest of these is Ceres ($D \approx 900$ km; see Figure 18). Travis & Schubert (2005) have shown that chondritic bodies of 100 km diameter undergo vigorous hydrothermal convection for millions of years if they accrete early. Ceres’ evolution thus depends on its composition and the timing of its accretion (McCord & Sotin 2005). Its global figure (Thomas et al. 2005) is indicative of gravitational relaxation and differentiation. With a derived bulk density of $\sim 2–2.5$ g/cm$^3$ (Michalak 2000), Ceres is speculated to be at least $\sim 1/3$ water by mass, and thus perhaps even a trans-Neptunian escapee. Ceres shows spectroscopic evidence for a complex geologic history forming carbonates and clays (Rivkin et al. 2006).

The view that Ceres is a planet is likely to prevail once NASA’s Dawn mission arrives in 2015 (Russell et al. 2004) to begin its imaging, spectrometry, and gravity science campaigns. As for Vesta—“the smallest terrestrial planet” (Keil 2002)—our perspective will also change when Dawn arrives in 2011. Figure 1 shows the overwhelmingly large mass of Vesta compared to garden-variety asteroids. Yet Vesta it is more intimately linked to asteroids than is Ceres, having its own clearly recognizable taxonomic and dynamical family (see Burbine et al. 2002). Why Ceres has no asteroid family, whereas Vesta does, is a mystery for another day.

Vesta has undergone global-scale volcanism as known from its basaltic spectral signature (V-type) and its clear link to the HED (howardite, eucrite, and diogenite) basaltic achondrite meteorites. It is the principal member of a family of several hundred small asteroids (Binzel & Xu 1993) that may have formed during the disruptive event that defines Vesta’s southern hemisphere (Asphaug 1997).

Vesta is also the only known differentiated rocky asteroid to have survived the evolution of the main belt more or less intact. The next largest basaltic asteroid is 1459 Magnya ($D \approx 17$ km). Although fragments this large could have been ejected from Vesta’s mega-crater (Asphaug 1997), Magnya appears to be dynamically and spectroscopically distinct, perhaps an isolated relic of another disrupted planet.

**Differentiation:** the process by which a planet forms a core and mantle through the segregation of dense iron from silicate minerals.
In the main belt, hit-and-run collisions would have disrupted Vesta-sized bodies during the \( \sim 30 \) Ma period when Moon- to Mars-sized planets were found there (Chambers & Wetherill 2001). As long as these targets were around to be impacted by differentiated planetary embryos, the shredded remains of these impactors would be expected, their bits and pieces surviving as exotic asteroids and puzzling meteorites. In this manner, the puzzle of Vesta’s surviving crust can perhaps be explained, in that it is not required to have dodged the fusillade of mega-impacts that would have accompanied the catastrophic disruption of dozens of less fortunate iron meteorite parent bodies, and would have mixed Vesta’s crust back into its mantle. Perhaps there was no such fusillade: instead of dodging bullets, Vesta avoided colliding into larger bodies until they left the main belt.

3.5. Delivery to Near-Earth Space

Where an asteroid resides today is not usually where it was born. The same holds true for major planets, but asteroids are particularly prone to this gravitational dance. While the major planets are now dynamically stable on billion-year timescales, small asteroids keep migrating.

The Yarkovsky effect nudges small asteroids and meteoroids into resonances (Gladman et al. 1997, Farinella et al. 1998, Vokrouhlický & Farinella 2000) so that NEOs and meteorites provide a relatively complete representation of the geologic, physical, and chemical record of solar system history (Burbine et al. 2002). The physics of impacts introduces a systematic bias in that hard, rocky asteroids eject faster fragments, which can make it to Earth on shorter timescales (before they are disrupted). The stochastic nature of family-forming collisional events might introduce an even more fundamental bias. The prevalence of young dynamical families confirms that today’s NEOs are, by and large, discrete samplings of catastrophic disruption events in the main belt that happened thousands to millions of years ago. With the discovery of extensive fossil beds of meteorites (Schmitz et al. 2003) it is incontrovertible that the meteoroid flux is punctuated by recent disruptions. The sampling of meteorites on Earth, and of small asteroids near Earth, reflects that bias.

4. CONCLUSIONS

Looking from Earth we can see a few thousand discrete stars by naked eye on a dark clear night. A backyard telescope reveals millions. Planets have been found around many of these stars, and through observations of planetary transits we may soon acquire direct detections of Earth-like worlds. Whether Earths are common depends in no small part upon the behavior of accreting planetesimals. Nearly all of the original mass of our main belt was swept up in the chaos of planet formation, so we may be fortunate not to have lost everything from our habitable zone.

As a spacefaring species, we can still review our history of asteroid missions in a single paragraph. It began when Mariner and Viking encountered Phobos and Deimos, captured asteroids or native moonlets later observed by other Mars missions. Galileo en route to Jupiter acquired the first detailed images of main-belt asteroids, 951 Gaspra and 243 Ida, the latter accompanied by the first confirmed small-body satellite, Dactyl. There have been subsequent asteroid flybys. The first asteroid rendezvous was NEAR, which flew by 243 Mathilde (the largest asteroid and only C-type yet visited) and went on to spend a year at 433 Eros. The second asteroid rendezvous was Hayabusa at Itokawa in late 2005, from whose surface a small sample may be on its way to Earth. Dawn is on its way, arriving at Vesta in 2011 and Ceres in 2015.

Our understanding of asteroids is biased toward those objects that we have studied in detail: the near-Earth S-types Itokawa and Eros. Chondritic and primitive asteroids are more representative,
and of these we have had a flyby look at one. As for the upcoming Rosetta flyby of Lutetia, and Dawn’s discoveries at Vesta, we will be, as ever, surprised by their novelty and reminded that the study of asteroids is just beginning.

**DISCLOSURE STATEMENT**

The author is not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

**ACKNOWLEDGMENTS**

This review is dedicated to Steve Ostro (1943–2008), champion of asteroid radar astronomy. Writing and research were sponsored by NASA’s Planetary Geology and Geophysics Program and by the University of California, Santa Cruz. I am grateful to my colleagues for generously sharing their ideas and artwork, and I regret the errors and omissions that are inevitable in a long review. I thank Katherine Armstrong for assistance in manuscript preparation.

**LITERATURE CITED**


Leinhardt ZM, Richardson DC, Quinn T. 2000. Direct N-body simulations of rubble pile collisions. *Icarus* 146:133–51


Wood JA. 1964. The cooling rates and parent planets of several iron meteorites. *Icarus* 3:429–59


# Contents

Where Are You From? Why Are You Here? An African Perspective on Global Warming  
*S. George Philander*  

Stagnant Slab: A Review  
*Yoshio Fukao, Masayuki Obayashi, Tomoeki Nakakuki, and the Deep Slab Project Group*  

Radiocarbon and Soil Carbon Dynamics  
*Susan Trumbore*  

Evolution of the Genus *Homo*  
*Ian Tattersall and Jeffrey H. Schwartz*  

Feedbacks, Timescales, and Seeing Red  
*Gerard Roe*  

Atmospheric Lifetime of Fossil Fuel Carbon Dioxide  
*David Archer, Michael Eby, Victor Brovkin, Andy Ridgwell, Long Cao, Uwe Mikolajewicz, Ken Caldeira, Katsumi Matsumoto, Guy Munhoven, Alvaro Montenegro, and Kathy Tokos*  

Evolution of Life Cycles in Early Amphibians  
*Rainer R. Schoch*  

The Fin to Limb Transition: New Data, Interpretations, and Hypotheses from Paleontology and Developmental Biology  
*Jennifer A. Clack*  

Mammalian Response to Cenozoic Climatic Change  
*Jessica L. Blois and Elizabeth A. Hadly*  

Forensic Seismology and the Comprehensive Nuclear-Test-Ban Treaty  
*David Bowers and Neil D. Selby*  

How the Continents Deform: The Evidence from Tectonic Geodesy  
*Wayne Thatcher*  

The Tropics in Paleoclimate  
*John C.H. Chiang*
<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rivers, Lakes, Dunes, and Rain: Crustal Processes in Titan’s Methane Cycle</td>
<td>299</td>
</tr>
<tr>
<td>Planetary Migration: What Does it Mean for Planet Formation?</td>
<td>321</td>
</tr>
<tr>
<td>The Tectonic Framework of the Sumatran Subduction Zone</td>
<td>345</td>
</tr>
<tr>
<td>Microbial Transformations of Minerals and Metals: Recent Advances in Geomicrobiology Derived from Synchrotron-Based X-Ray Spectroscopy and X-Ray Microscopy</td>
<td>367</td>
</tr>
<tr>
<td>The Channeled Scabland: A Retrospective</td>
<td>393</td>
</tr>
<tr>
<td>Growth and Evolution of Asteroids</td>
<td>413</td>
</tr>
<tr>
<td>Thermodynamics and Mass Transport in Multicomponent, Multiphase H₂O Systems of Planetary Interest</td>
<td>449</td>
</tr>
<tr>
<td>The Hadean Crust: Evidence from &gt;4 Ga Zircons</td>
<td>479</td>
</tr>
<tr>
<td>Tracking Euxinia in the Ancient Ocean: A Multiproxy Perspective and Proterozoic Case Study</td>
<td>507</td>
</tr>
<tr>
<td>The Polar Deposits of Mars</td>
<td>535</td>
</tr>
<tr>
<td>Shearing Melt Out of the Earth: An Experimentalist’s Perspective on the Influence of Deformation on Melt Extraction</td>
<td>561</td>
</tr>
<tr>
<td><strong>Indexes</strong></td>
<td></td>
</tr>
<tr>
<td>Cumulative Index of Contributing Authors, Volumes 27–37</td>
<td>595</td>
</tr>
<tr>
<td>Cumulative Index of Chapter Titles, Volumes 27–37</td>
<td>599</td>
</tr>
<tr>
<td><strong>Errata</strong></td>
<td></td>
</tr>
<tr>
<td>An online log of corrections to <em>Annual Review of Earth and Planetary Sciences</em> articles may be found at <a href="http://earth.annualreviews.org">http://earth.annualreviews.org</a></td>
<td></td>
</tr>
</tbody>
</table>