Characteristics of the Asteroid Population

- Jupiter interfered with the growth of a full sized planet in the asteroid belt.
  - Several protoplanets / “parent bodies” grew to modest size.
  - Subsequent collisions ground down this population to a distribution of object sizes dominated by the smaller ones.
    - The present-day mass contained in the asteroid belt is likely less than 1% of the original mass.
  - Ceres and Vesta are considered likely intact survivors and targets for the Dawn mission
  - Parent bodies were large enough to differentiate, likely heated by the decay of radioactive $^{26}$Al to $^{26}$Mg.
Asteroid Size Distribution

[Graph showing the cumulative number of asteroids against diameter, with the main asteroid belt and two family groups highlighted.]
Meteorite Composition/Characteristics

- Some meteorites are entirely metallic (about 5% of falls), some are rocky (95% of falls).
  - Metallic (iron) meteorites are evidence that large parent bodies differentiated and were subsequently shattered.
- Some strange meteorites include those likely to come from asteroids that have never differentiated (carbonaceous chondrites) and those that come from surfaces of volcanically active worlds (e.g. the eucrites which originate from Vesta).
  - Carbonaceous chondrites are rich in organic compounds including amino acids.
TABLE 6-2 Classification of Meteorites

<table>
<thead>
<tr>
<th>Broad classification</th>
<th>Group name assigned by Wasson a</th>
<th>Mineralogical-structural name</th>
<th>Percentage of falls b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primitive Bodies</td>
<td>Chondrites 86%</td>
<td>Carbonaceous chondrites 5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CM = C1</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO, CV = C2 = CII</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Stones 95%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ordinary chondrites 81%</td>
<td>E = Enstatite</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H = Bronzite</td>
<td>32.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L = Hypersthene</td>
<td>39.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LL = Amphoterite</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Others</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Achondrites 9%</td>
<td>Ureilites = Olivine-pigeonite</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aubrites = Enstatite</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diogenites = Hypersthene</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Howardites and eucrites</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Others = Other differentiated stones</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mesosiderites = Mesosiderites</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pallasites = Pallasites</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stony irons 1%</td>
<td>IA = Medium and coarse octahedrites</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IIA = Hexahedrites</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IIIA = Medium octahedrites</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IVA = Fine octahedrites</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Others = Ataxites, etc.</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Irons 4%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

99.9%
Widmanstatten Patterns

- Iron meteorites exhibit internal crystalline structure resulting from slow cooling.
  - Rates of approximately 50 degrees per million years are required to grow these crystals. Objects need to be several hundred kilometers in diameter to provide these cooling rates.

Fig. 2. Cooling rate curves based on two different mechanisms for the formation of the Widmanstatten pattern in Duchesne iron meteorite (IVA). Experimental data (circle dot) are from Moren et al. [6].
Pallasites

- Pallasites, or stony-iron, meteorites are thought to originate from the core-mantle boundary of differentiated parent bodies.
Chondrites

• The vast majority of falls are “stones” of chondritic composition.
  – That is they are substantially composed of fused glassy beads (called chondrites) whose origin remains controversial.

http://arxiv.org/pdf/1204.0739v1
Carbonaceous Chondrites

- These meteorites represent only a few percent of falls and are thought to originate from undifferentiated bodies from the wetter outer asteroid belt.
  - They are rich in carbon compounds (organic molecules) including amino acids.
  - The amino acids exist in both chiralities demonstrating an extraterrestrial origin.
Asteroid Distribution

- There are a few hundred thousand known asteroids mainly residing in the “asteroid belt” between Mars and Jupiter.
Kirkwood Gaps and Orbital Resonance

Main Asteroid Belt Distribution
Kirkwood Gaps

- Semi-major Axis (AU)
  - 2 to 2.1
  - 2.2 to 2.3
  - 2.4 to 2.5
  - 2.6 to 2.7
  - 2.8 to 2.9
  - 3.0 to 3.1
  - 3.2 to 3.3
  - 3.4 to 3.5

- Asteroids (per 0.005 AU bin)
  - 0 to 5
  - 6 to 10
  - 11 to 15
  - 16 to 20
  - 21 to 25
  - 26 to 30
  - 31 to 35
  - 36 to 40
  - 41 to 45
  - 46 to 50
  - 51 to 55
  - 56 to 60
  - 61 to 65
  - 66 to 70
  - 71 to 75
  - 76 to 80
  - 81 to 85
  - 86 to 90
  - 91 to 95
  - 96 to 100
  - 101 to 105
  - 106 to 110
  - 111 to 115
  - 116 to 120
  - 121 to 125
  - 126 to 130
  - 131 to 135
  - 136 to 140
  - 141 to 145
  - 146 to 150

- Resonances indicated:
  - 3:1
  - 5:2
  - 7:3
  - 2:1
Sometimes a Gap is Just a Gap

- The embedded satellite Daphnis clears the Keeler gap near the outer edge of Saturn's A ring. Pan clears the Encke gap.
Inclination vs. Semi-major axis
Asteroid Families
The Edgeworth/Kuiper Belt represents a distant population of small bodies (that includes Pluto). Resonances sculpt this population and provide some record of the orbital migration of the outer planets.

Resonances now contain trapped particles (representing locations where particles can remain relatively unperturbed – things are arranged to keep them and Neptune relatively far apart at the time of closest encounter).


FIGURE 11.5 (a) Orbital inclination as a function of semimajor axis for all known TNOs. Vertical dotted lines are drawn at the 3:2 and 2:1 orbital resonance with Neptune. (b) Orbital eccentricity as a function of semimajor axis. Solid curved lines are drawn for orbits with perihelia of $q = 30$ AU and $q = 35$ AU.
Trans-Neptunian objects

- Kuiper Belt
  - Haumea
  - Makemake
  - Orcus
  - Pluto

- Scattered disk
  - 2002 TX$_{300}$
  - 2004 XR$_{190}$
  - 2006 OH$_{181}$
  - 2007 UK$_{26}$

- Centaurs
  - Chariklo
  - Chiron
Ceres and Vesta

- The Dawn spacecraft has just completed an investigation of Vesta from orbit and will arrive at Ceres in February 2015.
Hydrostatic Equilibrium

Not Round

Nearly round

VESTA
(Dawn spacecraft)
Rotation axis also shown

EROS
(NEAR spacecraft)

CERES
(Hubble Space Telescope)
Hydrostatic Equilibrium

Pressure gradient in interior:

\[
\frac{dP}{dr} = -\rho g = -\frac{GM(r)\rho}{r^2}
\]

where \( M_r \) is the mass inside radius \( r \).

\[
M(r) = \int_0^r \rho(r) 4\pi r^2 \, dr
\]

Assuming constant density \( \rho \),

\[
M(r) = \frac{4\pi}{3} \rho r^3
\]
Substituting this expression for mass into the equation for hydrostatic equilibrium:

\[ dP = -\frac{4\pi}{3} \rho^2 G r \, dr \]

Integrating between \( r = 0 \) and where \( P = P_c \) (central pressure) and \( r = R \), radius of the moon where \( P \sim 0 \):

\[
\int_{P_c}^{0} dP = -\frac{4\pi}{3} \rho^2 G \int_{0}^{R} r \, dr
\]

\[
P_c = \frac{2\pi}{3} \rho^2 G R^2
\]

Saturn's moon Helene
43 km
For a material with “strength,” $S$, the critical radius $R$ at which the pressure is just great enough to overcome the compressional strength and squeeze the body into a sphere is found by $P_c \sim S$ and solving for $R_{sph}$

\[ R_{sph} = \sqrt{\frac{3S}{2\pi G}} \frac{1}{\rho} \]

$S$ is strength of material, rock or ice. For ice, $S = 1 \times 10^7 \text{ N/m}^2$

10 MPa

For rock, $S = 2 \times 10^8 \text{ N/m}^2$

200 MPa
Asteroid Distribution – The Red Dots
Near-Earth Asteroid Distribution

- There are thousands of Mars crossing (Amor) and Earth crossing (Apollo) asteroids – with lifetimes of 10 – 100 million years.
  - Lifetime is limited by collision with a terrestrial planet or extreme scattering.
Asteroids vs. Earth

- The Earth is struck by objects roughly representative of the size spectrum of asteroids – dust-sized particles constantly & 10 kilometer diameter objects every 100 million years. There are two primary delivery mechanisms:
  - Resonant orbit modification (ejection from Kirkwood Gaps)
  - Poynting-Robertson drag (light pressure on small particles)
- Accumulated mass is about 100 tons per day – almost all in the form of microscopic grains.
Mass Extinctions

- A 10 km diameter asteroid carries the kinetic energy of a million nuclear explosions, enough to cast Earth into a decade long “twilight” - global collapse of the food chain, mass starvation.
- Such objects are expected every 100 million years.
- By the way, watch out for the 300 meter diameter objects!
Mass Extinctions

- A 10 km diameter asteroid carries the kinetic energy of a million nuclear explosions, enough to cast Earth into a decade long “twilight” - global collapse of the food chain, mass starvation.

- Such objects are expected every 100 million years.

- By the way, watch out for the 300 meter diameter objects!

![Diagram showing the frequency of impactors of different sizes over time and their scales.](image)
Impacts Close to Home

35 million years ago...

Figure 1. Map showing the location of the Eyreville drill site in the Chesapeake Bay impact structure.
Mass Extinctions

- The fossil / geologic record points to repeating extinction events often correlated with the presence of iridium (a siderophile) in the Earth's crust.
- The Cretaceous/Tertiary (KT) boundary is such a layer correlated directly with the disappearance of the dinosaurs.
The K-T Boundary

- The fossil/geologic record points to repeating extinction events often correlated with the presence of iridium (a siderophile) in the Earth's crust.
- The Cretaceous/Tertiary boundary is such a layer correlated directly with the disappearance of dinosaurs.
A Smoking Gun

- The Chixulub impact structure dates to 65 million years ago – the disappearance of the dinosaurs.
Protecting the Earth

- Given enough lead time....

NO, but it makes great theater...
Nudging Asteroids

- Find asteroids sufficiently in advance (decades before impact) so that changing velocity by a millimeter per second will turn a direct hit into a near miss.
- A nearby nuclear nudge or the steady weak tug of a “gravity tractor” can do the job.
Gravity Tractor Physics

![Diagram of Gravity Tractor](image)

Figure 1. The schematic geometry of a Gravity Tractor towing an asteroid. If the distance $d$ between the centers of gravity of the asteroid and GT is equal to $1.5 \, r$ and the half-plume angle $\phi$ is assumed to be 20 degrees the engines will each have to be canted outward by 60 degrees and each will have to produce thrust equal to the towing force $T$.

<table>
<thead>
<tr>
<th>Gravity Tractor Performance</th>
<th>2004VD17</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Apophis</strong></td>
<td></td>
</tr>
<tr>
<td>( M = 4.6 \times 10^{10} \text{ Kg} )</td>
<td>( M = 2.6 \times 10^{11} \text{ Kg} )</td>
</tr>
<tr>
<td>( m = 1 \times 10^{8} \text{ Kg} )</td>
<td>( m = 1 \times 10^{3} \text{ Kg} )</td>
</tr>
<tr>
<td>( d = 1.5 , r = 240 \text{ meters} )</td>
<td>( d = 1.5 , r = 435 \text{ meters} )</td>
</tr>
<tr>
<td>( \Theta = 20 \text{ degrees} )</td>
<td>( \Theta = 20 \text{ degrees} )</td>
</tr>
<tr>
<td>( T = 0.053 \text{ Newtons} )</td>
<td>( T = 0.092 \text{ Newtons} )</td>
</tr>
<tr>
<td>( \Delta V = 3.7 \times 10^{-5} \text{ m/sec/year} )</td>
<td>( \Delta V = 1.1 \times 10^{-5} \text{ m/sec/year} )</td>
</tr>
<tr>
<td>( \Delta V_{\text{req}} = 2 \times 10^{-6} \text{ m/sec} )</td>
<td>( \Delta V_{\text{req}} = 5 \times 10^{-6} \text{ m/sec} )</td>
</tr>
<tr>
<td>Deflection ( T_{\text{req}} = 20 \text{ days} )</td>
<td>Deflection ( T_{\text{req}} = 163 \text{ days} )</td>
</tr>
<tr>
<td>Fuel(_{\text{req}} = \sim 10 \text{ kg} )</td>
<td>Fuel(_{\text{req}} = 83.9 \text{ kg} )</td>
</tr>
</tbody>
</table>

Figure 2. Performance figures for a 1 metric ton Gravity Tractor powered by solar electric propulsion in deflecting asteroids 99942 Apophis and 2004VD17, the two NEOs in the current database with the highest probabilities of Earth impact. (M, asteroid mass; m, spacecraft mass; d, hovering distance from asteroid centroid; $\phi$, half angle of ion propulsion plume; T, thrust required to hover; $\Delta V$, deflection acceleration; $\Delta V_{\text{req}}$, velocity change required to avoid Earth impact)
Light Momentum and Solar Sailing

- The momentum carried by a photon is proportional to its energy. The solar flux at Earth corresponds to a force, \( \frac{dp}{dt} \), of 10\( \mu \)N/m\(^2\) for a reflective sail.

- For a sail 32 meters across with a 100 kg total mass, \( \Delta V \) is 3 km/sec in one year of solar acceleration (at Earth).

\[
p_{\text{absorb}} = \frac{E}{c}
\]
\[
p_{\text{reflection}} = 2\frac{E}{c}
\]
The Zodiacal Light and Poynting-Robertson Drag

- Asteroid collisions (and comets) produce a significant population of small dust grains, visible to the unaided eye as the “zodiacal light.”

- What happens to these small grains?
Radiative Blowout

- If radiation pressure force exceeds gravitational force the particle gets “blown” away.

\[ F_{\text{rad}} = \frac{L_{\text{sun}}}{4 \pi r^2} Q (\pi a^2) \frac{1}{c} = \frac{L_{\text{sun}}}{4c} \frac{a^2}{r^2} Q \]

\[ F_{\text{grav}} = \frac{GM_{\text{sun}} m_{\text{grain}}}{r^2} = \frac{GM_{\text{sun}}}{r^2} \frac{4 \pi a^3 \rho}{3} \]

Note that these equations have both been cast in terms of the grain size, \( a \), since we want to looks at how the ratio between the two forces changes with grain size.

\( Q \), above, is an adjustment between physical cross section for a particle and the way it actually behaves. In particular small grains couple poorly to long wavelength photons (wavelengths bigger than the grain size), so they have smaller cross sections than their geometrical cross section. For example very tiny grains (Rayleigh scattering) have \( Q \sim \left( \frac{a}{\lambda} \right)^4 \).
Radiative Blowout

- If radiation pressure exceeds gravity the particle gets “blown” away.

- For “big” grains, radiation pressure increases relative to gravity inversely with grain size, reaching parity at just the wavelength where Q begins to kick in.

\[
\frac{F_{\text{rad}}}{F_{\text{grav}}} = \frac{3}{16\pi} \frac{L_{\text{sun}}}{GM_{\text{sun}} c} \frac{Q}{\rho a}
\]

\[
= 0.58 \left( \frac{1000 \text{ kg/m}^3}{\rho} \right) \left( \frac{1 \mu m}{a} \right) Q
\]

\[
Q = 1 \quad \text{Huge}
\]

\[
Q \sim \left( \frac{a}{\lambda} \right)^{1-2} \quad \text{Comparable}
\]

\[
Q \sim \left( \frac{a}{\lambda} \right)^{4} \quad \text{Tiny}
\]

- Once the particle size becomes small compared with the wavelength, grain size enters the numerator and radiation pressure decreases relative to gravity as the particle couples more and more poorly to the radiation.
Comet Tails

- Dust pushed back by solar radiation pressure and ionized gas blown back by solar wind.
Meteor Showers

- Meteor showers originate from coherent streams of particles shed from comets – the particles spread out along the orbit.
- Since the particles are on parallel paths they appear to originate from a common point in the sky.
- The next big shower is the Geminids - Dec 13/14
Poynting-Robertson Drag

- A particle moving in orbit at velocity, $v$, around a light source will see light/momentum coming artificially from the forward direction in proportion to $v/c$ – think rain hitting a vertical windshield, or recall the aberration of starlight.

- The angle at which the raindrops (photons) strike is
  \[ \sin \theta \approx \theta = \frac{v}{c} \]

- The momentum per unit time imparted against the direction of motion (assuming absorption) is
  \[ \frac{\Delta p}{\Delta t} = F_{\text{rad}} \sin \theta = \frac{\text{Flux}_{\text{intercepted}}}{c} \frac{v}{c} \]

- A particle in circular orbit about the Sun will see a torque \((r \times p)\) opposing its orbital angular momentum. In scalar terms
  \[ \frac{dL}{dt} = r \frac{L_{\text{sun}}}{4\pi r^2 c} Q \pi a^2 \left| \frac{v}{c} \right| = \frac{L_{\text{sun}}}{4c^2} Qa^2 \frac{v}{r} \]
Poynting-Robertson Timescale

- In the simple case, the velocity on the previous page is circular orbital velocity.

\[
\frac{dL}{dt} = \frac{L_{\text{sun}}}{4c^2} Q a^2 \frac{v}{r} = \frac{L_{\text{sun}}}{4c^2} Q a^2 \left( GM_{\text{sun}} \right)^{1/2} r^{-3/2}
\]

also \( L = m v r \) so

\[
\frac{dL}{dt} = \frac{d}{dt} \left( m \sqrt{\frac{GM_{\text{sun}}}{r}} r \right) = m \left( GM_{\text{sun}} \right)^{1/2} \frac{1}{2} r^{-1/2} \frac{dr}{dt}
\]

\[
m \left( GM_{\text{sun}} \right)^{1/2} \frac{1}{2} r^{-1/2} \frac{dr}{dt} = \frac{L_{\text{sun}}}{4c^2} Q a^2 \left( GM_{\text{sun}} \right)^{1/2} r^{-3/2}
\]
Poynting-Robertson Timescale

- Integrating, the time for a particle to spiral in is

\[
    t_{pr} \approx 700 \text{ years} \left( \frac{a}{1 \text{ AU}} \right)^2 \left( \frac{\rho}{1000 \text{ kg/m}^3} \right) \left( \frac{a}{1 \mu m} \right)
\]

Even 1 mm particles disappear in only 700,000 years. Meter size particles are removed in a billion years.

Poynting-Robertson drag can move stuff around.
Implications for Extra-solar Systems

- Debris disks (seen via the surface area in the tiny particles) around nearby stars observed with Hubble must be *actively replenished*. Suggests the existence of debris belts like the asteroid and Kuiper belts in our own Solar System.
The Yarkovsky Effect

- Pressure from emitted radiation can also be a source of propulsion for big (kilometer sized) asteroids.

- Asteroids are warmed by the Sun, as they rotate the hottest radiating point is on the “afternoon” side, producing a component of force along the asteroid orbit.

- This effect causes smaller asteroids to migrate toward Kirkwood resonances, casting them into unstable orbits (target Earth).

\[
\frac{A \sigma T^4}{C}
\]
Moving Asteroids to Resonance

![Graph showing asteroid distribution](http://www.nature.com/nature/journal/v449/n7158/pdf/nature06070.pdf)

**Figure 1** The orbital and size distribution of the observed Baptistina asteroid family. The family has been projected onto a plane of proper semimajor axis \( a \) versus absolute magnitude \( H \). On the right ordinate, we show asteroid diameters for a typical C-type asteroid albedo of 0.04. The central and largest body of the family, C-type asteroid (298) Baptistina\(^9\), has proper semimajor axis \( a = 2.264 \) au, eccentricity \( e = 0.15 \), and sine of inclination \( i = 0.10 \) (ref. 18). The BAF was identified using the hierarchical clustering method (HCM) applied to the proper orbital element database found in the AstDyS database\(^8\) (see Supplementary Discussion). The HCM locates bodies in the neighbourhood of (298) Baptistina with mutual velocities less than a threshold limit \( V_{\text{cutoff}} \). The filled and open circles show 3,042 linked objects with \( V_{\text{cutoff}} = 53 \) m s\(^{-1}\). The family is also noticeably depleted near the adjacent \( j/2 \) and \( M5/9 \) resonances\(^9\) (grey bar at \( a \approx 2.2545 \) au). The two-lobed structure with an evacuated centre is diagnostic of families that have spread in \( a \) for an extended time under the influence of Yarkovsky/YORP thermal forces\(^{21,22}\). The dark grey lines that bracket the outside of each lobe represent our best estimate of how far the majority of family members could have spread in \( \sim 160 \) Myr. Objects outside these curves, shown as open circles, are assumed to be predominantly interlopers. Most come from the nearby Flora or Vesta families, whose spectroscopic signatures are similar to space-weathered ordinary chondrites (that is, S-type asteroids; Flora family) or basaltic achondrites (HED) meteorites (that is, V-type asteroids; Vesta family)\(^{19,43,45}\). Their number density near a \( H \) of \( \sim 16 \), at which the SDSS is sensitive to asteroids, indicates that interlopers between the grey curves only contribute 10–20% to the overall BAF.