Small Bodies in the Solar System

• So far, we’ve covered larger bodies, with masses $> 0.003 \, M_⊕$
  – The Sun
  – The planets (terrestrial and Jovian)
  – The major satellites
    • Moon, Io, Europa, Ganymede, Callisto, Titan, Triton
Small Bodies in the Solar System

• There are also mid-size objects (10^{-10} to 0.003 \ M_⊕)
  – Asteroids
    • Rocky, metallic (1.5 < a < 5.2 AU)
  – Trans-Neptunian Objects (TNOs)
    • Icy, rocky (a > 30 AU)

• There are also many smaller bodies that we’ll collectively call meteroids.
Asteroids

- *Asteroids* (also formerly known as *minor planets*) were discovered as a result of a search for a “missing planet”, stimulated by *Bode’s Law*.
- Bode’s Law is not a law in the sense of Newton’s Laws, or even Kepler’s Laws; it’s just numerology (as far as we know....)
Bode’s Law

- Start with $N = 0$, then $N = 3$. Double $N$, add 4, divide by 10.

$$(N + 4)/10 = D(\text{AU})$$
## Bode’s Law

<table>
<thead>
<tr>
<th>Bode's Formula</th>
<th>Distance</th>
<th>Planet</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0+4)/10</td>
<td>0.4</td>
<td>0.39 Mercury</td>
</tr>
<tr>
<td>(3+4)/10</td>
<td>0.7</td>
<td>0.72 Venus</td>
</tr>
<tr>
<td>(6+4)/10</td>
<td>1.0</td>
<td>1.00 Earth</td>
</tr>
<tr>
<td>(12+4)/10</td>
<td>1.6</td>
<td>1.5 Mars</td>
</tr>
<tr>
<td>(24+4)/10</td>
<td>2.8</td>
<td>?</td>
</tr>
<tr>
<td>(48+4)/10</td>
<td>5.2</td>
<td>5.2 Jupiter</td>
</tr>
<tr>
<td>(96+4)/10</td>
<td>10.0</td>
<td>9.5 Saturn</td>
</tr>
<tr>
<td>(192+4)/10</td>
<td>19.6</td>
<td>19.2 Uranus</td>
</tr>
</tbody>
</table>
Bode’s Law

- Bode’s Law seemed to explain distances of known planets in 1800, but left a gap at 2.8 AU.
- Planets can be searched for by trying to detect motion relative to the background stars.
Discovery of Asteroids

• Searches for objects that move relative to the background stars led on 1 January 1801 to discovery of Ceres, at $a = 2.8$ AU!
• A second small body was discovered in 1802, and more followed.
• By 1890, more than 300 were known.
• These became known as “minor planets” or “asteroids”.
Asteroids

- Orbits of about 2000 asteroids have been determined.
  - A careful search could turn up more than 100,000, mostly between Mars and Jupiter
### Size Distribution of Asteroids

<table>
<thead>
<tr>
<th>Number</th>
<th>Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Ceres)</td>
<td>1000 km</td>
</tr>
<tr>
<td>200</td>
<td>100 – 1000 km</td>
</tr>
<tr>
<td>500</td>
<td>50 – 100 km</td>
</tr>
</tbody>
</table>
Sizes of Asteroids

Ida and its satellite Dactyl

HST image of Ceres
Mass Distribution of Asteroids

- Ceres
- Vesta
- Pallas
- Hygiea
- Euphrosyne
- Interamnia
- Davida
- Herculina
- Eunomia
- Juno
- Psyche
- Europa
- Other
Composition of Asteroids

• Asteroids are made of rocky and metallic material.
  – No ices since they are too close to Sun.
  – They would be much brighter if they had icy surfaces.
Water ice sublimates

Saturn

Jupiter

Mars

CO$_2$ sublimates
Composition of Asteroids

- Asteroids are made of rocky and metallic material.
  - No ices since they are too close to Sun.
  - They would be much brighter if they had icy surfaces.
  - Optical/infrared spectra show that they are similar to meteorites found on the Earth.
Spectra of Asteroids and Meteorites
Orbits of Asteroids

• Perturbations by Jupiter remove asteroids from orbits that are in resonance with Jupiter.
  – These are *Kirkwood Gaps*.
  – Ratio of orbit period of Jupiter to orbital periods in Kirkwood gaps are integers or ratio of two integers.
Distribution of Asteroids
Orbits of Asteroids

- Some asteroids are in orbits that are identical to Jupiter’s, but lead Jupiter or follow Jupiter by 60°.
  - These are called the **Trojan** asteroids.
  - The points 60° from Jupiter are two of the five quasi-stable *Lagrangian points*.
- Earth-crossing asteroids are known as **Apollo** asteroids.

Orbits of 7 of the 31 known Apollo asteroids are shown.
Pluto: The First Known TNO

- Pluto was discovered in 1930 as a result of a concentrated search for a ninth planet.
Pluto and Charon

- Extreme orbital characteristics:
  - larger orbit than the major planets
    - semimajor axis $a = 39.4$ AU
    - higher inclination ($i = 17^\circ.15$)
    - higher eccentricity ($e = 0.249$)
    - aphelion distance = 49.2 AU
    - perihelion distance = 29.6 AU
    - Neptune’s distance from Sun = 30.1 AU
    - From 1979 – 1999, Neptune was farther from the Sun than Pluto!
Neptune
Uranus
Saturn
Jupiter
Pluto
Can Pluto and Neptune Collide?

- Note that their orbital periods are a near 3:2 resonance:
  - Sidereal period of Neptune: 163.72 years
    - (× 3 = 491 years)
  - Sidereal period of Pluto: 248.021 years
    - (× 2 = 496 years)
  - As seen from Neptune, the synodic period of Pluto is:

\[
\frac{1}{S} = \frac{1}{P_{\text{Neptune}}} - \frac{1}{P_{\text{Pluto}}} = \frac{1}{163.72} - \frac{1}{248.02} = \frac{1}{481.71}
\]

Conjunctions occur with planets in the same places in their orbits.

As seen from Neptune, oppositions of Pluto occur when Pluto is near its aphelion!
Pluto Does Not Cross the Path of Neptune!
Pluto and Charon

- *New Horizons* probe to Kuiper Belt launched in January 2006.
- Will arrive at Pluto/Charon in July 2015.
Pluto and Charon

- Double nature discovered in 1978
Pluto and Charon

- Orbital period $P = 6.4$ days
- Brightness variations imply that period of rotation is the same as period of revolution (i.e., tidally locked)
Eclipses

- Eclipses can be used to measure the sizes of Pluto and Charon.
- Kepler’s Third Law can be used to measure the masses of Pluto and Charon.
- Eclipses can be used to map the surfaces of Pluto and Charon.
Eclipses

Charon → Pluto

Brightness vs. Time
Eclipses

“First contact”

Eclipse begins
Eclipses

“Second contact”

Eclipse reaches minimum

Time

Brightness
Eclipses

“Third contact”

Eclipse begins to end
Eclipses

“Fourth contact”

Eclipse ends
Eclipse-Based Map of Pluto
Eclipse-Based Map of Charon
Space Telescope Photos

Pluto
PRC96-09a · ST ScI OPO · March 7, 1996 · A. Stern (SwRI), M. Buie (Lowell Obs.), NASA, ESA
## Masses and Sizes

<table>
<thead>
<tr>
<th>Property</th>
<th>Pluto</th>
<th>Charon</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mass</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earth = 1</td>
<td>0.0022</td>
<td>0.0003</td>
</tr>
<tr>
<td>Pluto = 1</td>
<td>1</td>
<td>0.14</td>
</tr>
<tr>
<td><strong>Diameter (km)</strong></td>
<td>2300</td>
<td>1300</td>
</tr>
<tr>
<td><strong>Density (g cm(^{-3}))</strong></td>
<td>1.8</td>
<td>1.2</td>
</tr>
</tbody>
</table>
Composition

• Densities of Pluto and Charon give clues to composition, which is primarily ices plus some rocky/metallic material.
• Pluto is very similar to Triton, the largest satellite of Neptune.
Surface Composition

• Pluto is surprisingly bright compared to other bodies with icy surfaces.
  – Long exposure of methane ice to solar UV radiation turns it dark.
  – This implies that methane partially vaporizes at perihelion, so surface ice is renewed.
  – Great temperature variation because of Pluto’s high eccentricity orbit
    • Perihelion (29.6 AU) temperature $T = 51$ K
    • Aphelion (49.2 AU) temperature $T = 40$ K
Is Pluto a Planet?

- Subject of intense debate over last decade.
- Status as “planet” increasingly jeopardized as additional large TNOs were found.
IAU Definition of “Planet”

1) It is in orbit around the Sun, not a satellite of another planet.

2) It has sufficient mass for its self-gravity to overcome its compressional strength (i.e., it is roughly spherical).

3) It has cleared its orbital neighborhood (orbital dominance).
IAU Definition of “Planet”

3) It has cleared its orbital neighborhood (orbital dominance).
   • Objects that don’t meet this criterion are called “dwarf planets”
   • Currently recognized dwarf planets are Eris, Pluto, Makemake, and Ceres.
The Kuiper Belt

- Most Kuiper Belt objects are planetesimal-sized bodies (cometary nuclei); Pluto and Triton are just particularly large.
- Charon was probably formed by a “giant impact” of a planetesimal with Pluto.
Comets

• Beyond Jupiter, icy bodies can survive in the vacuum of interplanetary space.

• However, if icy bodies approach closer to the Sun than \( \sim 4 \) – \( 6 \) AU, they begin to sublimate.
  – *Sublimation*: *solid* becomes *a gas*
  – Such icy bodies are *comets*. 
A Typical Comet

- Mass: 10 – 100 billion tons
- Size: 1– 10 km

Composition: “dirty iceberg”
Comet Structure

- The original icy body forms the “nucleus”.
Comet Structure

- Sublimation of the nucleus forms the *coma*, or atmosphere, of the comet.
- Escaping gases form *tails*.
Comet Tails

- “Gas” or “ion” tail:
  - Straight and narrow
  - Consists of ions swept up by solar wind
- “Dust” tail:
  - Wide and diffuse
  - Solid particles pushed by radiation pressure

Comet tails always point away from the Sun
Comet Tails

- Comet tails point away from the Sun
  - gas tail in direction of Solar wind
  - when comet leaves the inner Solar System, it goes tail first
8. Beyond about 6 AU comet is too cold for ice to sublimate, becomes inactive.


6. Comet receding from Sun. Tail still of dust and gas and still well developed.

5. Near perihelion comet most active, may fragment.

4. Comet very active around 1 AU. Coma of dust particles and gas. Tail may be 1–2 AU long.

3. Ice subliming, icy dust being blown off. Tail forming.

2. Most volatile ices begin to sublime, producing some gas around 4-6 AU.

1. Near aphelion, nucleus is inactive, may have surface layer enriched in dark dust.
Comet Tails

- Near the Sun, coma can expand to 100,000 km (but very low density).
- Tail can be millions of kilometers long (up to 1 – 2 AU in extreme cases).
Origin of Comets

• Characteristics to explain:
  1. High eccentricity orbits
     • $e \leq 1$ usually; sometimes $e \geq 1$
  2. Orbits randomly inclined to ecliptic
  3. Average semi-major axis of orbit $a = 25,000$ AU $\Rightarrow$ average orbital period $P = 4$ million years.
Oort Cloud

- The **Oort Cloud** is a "comet reservoir"
  - quasi-spherical distribution of icy bodies
  - centered on Sun
  - radius 50,000 AU
    - distance to nearest star is ~270,000 AU
The Oort Cloud

50,000 AU

The Sun, surrounded by a cloud of comets

270,000 AU

Nearest star
Formation of Comets

• Cometary bodies formed in pre-Solar nebula, about 20 – 30 AU from center
  – distance of Uranus and Neptune
  – temperature $T \approx 100 \text{ K}$
  • At higher temperature, ices do not survive.
  • A lower temperatures, $\text{H}_2\text{O}$ locked into solid hydrates of ammonia and methane.
Formation of Oort Cloud

• Perturbations by Uranus and Neptune scatter the orbits of the icy bodies:
  – smaller orbits $\Rightarrow$ sublimate quickly, don’t last.
  – large orbits $\Rightarrow$ form Oort Cloud
  – very large orbits $\Rightarrow$ escape from Solar System

• Detailed models predict “transjovian” icy bodies near the ecliptic $\Rightarrow$ **Kuiper Belt.**
How Do Comets Get Back to the Inner Solar System?

- Perturbations of cometary orbits by passing stars probably alter their orbits so they can re-enter the inner Solar System.
Periodic Comets

- Periodic comets are defined to be those with orbital periods $P < 200$ years
  - Implies aphelion distances $\leq 70$ AU.
- These are comets captured into a smaller orbit by Jupiter (or another planet).
Periodic Comets

• Capture of comet by Jupiter...
Comet Shoemaker-Levy 9 (SL/9)

- Captured by Jupiter in 1992
- Collided with Jupiter after first orbit
Comet SL/9

- First perijove fragmented the comet into several smaller pieces, all on the same orbit.
Comet SL/9

- Fragmented comet struck Jupiter in the summer of 1994
Comet SL/9

- Comet fragments hitting the upper cloud deck of Jupiter resulted in fireballs easily seen in the infrared.
Impact sites
A Crater Chain on Callisto

- A crater chain on Jupiter’s satellite Callisto shows that this kind of event has occurred before.
What Would a Similar Collision on Earth Look Like?

More on this later...
Comet P/Halley

- Comet Halley: most famous periodic comet.
  - Named after Edmund Halley (Astronomer Royal of Britain, friend of Newton, champion of Universal Gravitation).
Comet P/Halley

- $P \approx 76$ years
- $a \approx 17.9$ AU, so aphelion distance is about 36 AU
- Every return recorded since 240 BC (except 164 BC).
- Most recent return in 1986.
Orbit of Comet P/Halley
Clearing Out the Debris

Radiation Pressure and the
Poynting-Robertson Effect
Small Debris in the Solar System

- **Meteoroids** are small solid particles in the interplanetary medium as evidenced by zodiacal light.
  - Backscattered solar radiation
  - Origin: comets, asteroids
“False Dawn” of the Zodiacal Light
Meteors

- **Meteors** are meteoroids as they enter the Earth’s atmosphere and vaporize.
  - Typical size: 1 cm$^3$ (size of a sugar cube)
  - Typical altitude: 100 km
Meteorites

- *Meteorites* are more massive meteoroids (more than a few grams) that reach the ground intact.

**Stony:** asteroid-like material (90%)

**Iron:** metallic, up to 15% nickel
Meteor Speeds

- Evening meteors are slower than morning meteors as they must overtake the revolving Earth.

Morning meteors hit the leading side of the Earth

Evening meteors hit the trailing side of the Earth

Fastest: $42 + 30 = 72 \text{ km s}^{-1}$

Fastest: $42 - 30 = 12 \text{ km s}^{-1}$

To Sun
Meteor Showers

• When Earth crosses the path of a comet, a meteor shower occurs.

A time exposure of a few minutes.
Meteor Showers

• Annual meteor showers, like the famous “Perseids”, occur when meteoroids are distributed along the whole orbit.
• They are generally named after the constellation in which they appear to originate.
Perseid Meteor Shower
Meteor Showers

• Periodic meteor showers are those where the meteoroids are “clumped” in certain locations in the orbit; showers do not occur every year.
<table>
<thead>
<tr>
<th>Shower Name</th>
<th>Date of Maximum</th>
<th>Associated Comet</th>
<th>Comet Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lyrid</td>
<td>Apr 21</td>
<td>1861 I</td>
<td>415 yr</td>
</tr>
<tr>
<td>η Aquarid</td>
<td>May 4</td>
<td>Halley</td>
<td>76 yr</td>
</tr>
<tr>
<td>Perseid</td>
<td>Aug 11</td>
<td>1862 III</td>
<td>105 yr</td>
</tr>
<tr>
<td>Orionid</td>
<td>Oct 20</td>
<td>Halley</td>
<td>76 yr</td>
</tr>
<tr>
<td>Taurid</td>
<td>Oct 31</td>
<td>Encke</td>
<td>3 yr</td>
</tr>
<tr>
<td>Leonid</td>
<td>Nov 16</td>
<td>1866 I</td>
<td>33 yr</td>
</tr>
</tbody>
</table>
Leonids in 2001 at Ayres Rock, Australia
Leonids as seen from Earth Orbit
Meteors and Meteorites

• There are over 25 million observable meteors per day (but only about 100 from any one spot).
• Only one or two per day reach the ground intact.
• Earth accumulates 10 – 100 tons daily.
Nature of Meteorites

- Some meteorites are primitive bodies, undifferentiated
- Represent some of earliest solids in the Solar System

Arrow points to embedded metal flakes

Arrow points to solidified droplets
Nature of Meteorites

- Other meteorites are *processed*.
- Either metallic (from a planet’s core) or a result of volcanism (from a planet’s crust or mantle)
Composition of Meteorites

- Crystal patterns in iron-type give clues to formation
Origin of Processed Meteorites

• Formation at \( \sim 800 \) K
• Cooling at 1 – 10 K per million years \( \Rightarrow \) insulated, not comet-like bodies
• Cooling time as expected if covered with outer shell of rock \( \Rightarrow \) asteroids 300 – 600 km diameter.
Break-Up of a Differentiated Body
Origin of Processed Meteorites

• This meteorite, found in the Antarctic, is probably from Mars!
• Violent impact can remove small rocks from a planet.
• How do we know it’s from Mars?
  – Trapped gases inside have composition identical to Martian atmosphere.
• Meteorites from the Moon have also been identified.
How Can Meteorites Be Identified?

1) “Fall” observed by eyewitnesses.
Observation of a Fall

• This meteorite was observed to fall on a roof in Weston, CT, in 1807 December.
• Several witnesses.
• Substantiated by two Yale professors.

“Gentlemen, I would rather believe that two Yankee professors would lie than believe that stones fall from heaven.”

Thomas Jefferson
President of the United States
How Can Meteorites Be Identified?

1) “Fall” observed by eyewitnesses.
2) Collection on glaciers.
Origin of Meteorites

• Most *meteors* originate in comets.
• Most *meteorites* originate in asteroids.

• Gravitational scattering by Jovian planets can send small debris (comets and asteroids) on trajectories towards the Earth.
Jovian Planets Affect Earth Through Their Influence on Small Bodies.

Not to scale!

Oort cloud comets affected by passing stars can also strike Earth.

Asteroid and comet impacts affect geology and biology on Earth.

Jovian planet “nudges” send objects toward Earth and other planets.

Asteroid belt (2–3 AU): rocky leftovers of “frustrated planet formation” due to influence of Jupiter’s gravity

Kuiper belt (30–100 AU): icy leftovers of the outermost solar nebula; “sculpted” by orbital resonances with jovian planets

Oort cloud (out to 50,000 AU): icy planetesimals from the jovian planet region ejected by gravitational encounters
What Would Happen if a Similar Collision Occurred with Earth?
Can It Happen to You?

• “Ann Elizabeth Hodges (1923-1972) of Sylacquga, AL, is the only person of record to have been hit by a meteorite. On November 30, 1954, she was napping on her living room couch when a grapefruit-sized rock from space crashed through the roof of her house. It bounced off her large wooden console radio, destroying it, and struck her on the arm and hip. She was badly bruised but able to walk.”

4 kilogram culprit
Can It Happen to US?

A daytime fireball over Wyoming, August 1972
Identified Impact Sites on Earth
Barringer Meteor Crater

- Location: Northern Arizona
- Diameter: 1.186 kilometers (.737 miles)
- Age: 49,000 years
Wolfe Creek Crater

- Location: Wolfe Creek, Australia
- Diameter: 0.875 kilometers (.544 miles)
- Age: 300,000 years
Clearwater Lakes

- Location: Ontario, Canada
- Diameter:
  - Clearwater Lake West: 32 kilometers (20 miles)
  - Clearwater Lake East: 22 kilometers (13.7 miles)
- Age: 290 ± 20 million years
Cataclysmic Meteorite Impacts

• A large meteorite (~1 km in radius) at maximum impact velocity would have the explosive effect of nearly 10 million 1-Megaton bombs.
• Most likely impact site is ocean (covers 75% of Earth).
• Potentially damaging after-effects such as “nuclear winter”.
The K-T Event

• Cretaceous-Tertiary Mass Extinction, commonly known as the K-T Event, occurred 65 million years ago.

• Up to 99% of all organisms and 75% of all species (including all dinosaurs) disappeared fairly suddenly.

• Now widely thought to be due to a large meteorite impact.
The K-T Event

• Evidence:
  – Iridium-rich sediments in strata of age 65 million years.
  – World-wide phenomenon
  – Iridium rare on surface of Earth, common in meteorites.
  – A 10-km meteorite would be needed to account for all the iridium.
The K-T Event

- Likely impact site: Yucatan peninsula
  - 65 million year old, iridium rich crater discovered in the course of oil exploration
So, Doc, what are my chances?

- Statistically, they’re pretty good…

![Diagram showing typical time between impacts and impactor size](image-url)
Next: The Solar System in Perspective