Lecture 27: Comets & Asteroids

Comets Asteroids

Solar System Debris

- Interplanetary debris
  - Leftover from the formation of the Solar System
  - Ranges from large asteroids and comets to microscopic dust
  - Rocky material resembles the outer layers of the terrestrial planets
Solar System Debris

- Interplanetary debris
  - The total mass of the debris is less than that of the Moon
  - These objects are nearly unchanged since the formation of the Solar System

Comets

Comets are made of ice and rock, similar to the moons of the outer planets – they are also composed of ancient material.

Comets fall into two major groups, depending on the period of their orbits (short-period comets and long-period comets).

Comet Ikeya-Seki
Asteroids

- Asteroids are small, rocky bodies that orbit the Sun
- Most are smaller than 300 km in diameter
- Asteroids have eccentric orbits and spend the majority of their time in the asteroid belt between Mars and Jupiter
- The total mass of all asteroids is less than 1/10 the mass of Earth's Moon.

\[\begin{array}{cccc}
\text{Date} & \text{Rise} & \text{Mass} & \text{Orbit} \\
\text{Mars} & 0.38 & 0.05 & 0.25 \\
\text{Venus} & 0.39 & 0.09 & 0.01 \\
\text{Earth} & 0.50 & 0.10 & 0.04 \\
\text{Mars} & 0.50 & 0.11 & 0.04 \\
\text{Jupiter} & 0.31 & 0.01 & 0.01 \\
\text{Saturn} & 0.31 & 0.01 & 0.01 \\
\text{Uranus} & 0.21 & 0.01 & 0.01 \\
\text{Neptune} & 0.01 & 0.01 & 0.01 \\
\text{Pluto} & 0.01 & 0.01 & 0.01 \\
\end{array}\]

Ida and Dactyl
Gaspra
Asteroids

- The first asteroid discovered was Ceres, detected by Giuseppe Piazzi in 1801.
- The orbit of Ceres has semi-major axis of 2.8 AU.
- Within a few years, Pallas, Juno, and Vesta were discovered.
- Several hundred thousand asteroids have been discovered.
- Several thousand new discoveries are made each year.

<table>
<thead>
<tr>
<th>Name</th>
<th>Diameter</th>
<th>Semi-major axis</th>
<th>Eccentricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceres</td>
<td>940 km</td>
<td>2.8 AU</td>
<td>0.0789</td>
</tr>
<tr>
<td>Pallas</td>
<td>580 km</td>
<td>2.8 AU</td>
<td>0.2299</td>
</tr>
<tr>
<td>Vesta</td>
<td>525 km</td>
<td>2.4 AU</td>
<td>0.0895</td>
</tr>
<tr>
<td>Juno</td>
<td>240 km</td>
<td>2.7 AU</td>
<td>0.2579</td>
</tr>
</tbody>
</table>

- We are currently aware of over 4,000 asteroids with determined orbits.
- Most asteroids spend all their time between Mars and Jupiter in the Asteroid Belt, between 1.5 – 3.5 AU from the Sun.
- These large asteroids have relatively small eccentricities.
- NASA maintains an "Asteroid Fact Sheet" for selected objects:
Asteroids

- Asteroids that cross the orbit of Mars are called Amor Asteroids
  - about 1200 of them are known
- Asteroids that cross the orbit of Earth are called Apollo Asteroids
  - about 2000 of them are known

There are five locations in the solar system, called Lagrange points, where an asteroid can orbit in equilibrium with the Sun and Jupiter:

- L1, L2, and L3 are unstable
  - Asteroids located at L1, L2, or L3 would drift away...

\[ \text{Jupiter} \quad \text{Sun} \quad \text{L1} \quad \text{L2} \quad \text{L3} \]
Asteroids

The points L4 and L5 are stable - asteroids at these locations would remain there. Asteroids orbiting at the Lagrange points L4 and L5 are called the Trojan asteroids.

Asteroids

- Asteroids have two main classes of compositions: either carbon-rich or silicon-rich.
- Carbon-rich (C-type) asteroids are dark in color, and are more ancient.
- Silicon-rich (S-type) asteroids are light in color, and have probably been reprocessed.
Mathilde (about 25 km across)

**Asteroids**

- Asteroid surfaces display evidence for complex reprocessing
- Vesta is rich in pyroxine, which is commonly observed in lava flows on Earth
- Many meteorites have the same chemical composition, indicating that they are "chips" of Vesta
• Many asteroids, with eccentricities larger than about 0.4, cross the orbit of Earth – these are the Apollo Asteroids
• The minimum and maximum distances from the Sun are given by
  \[ D_{\text{perihelion}} = (1 - e) a \]
  \[ D_{\text{aphelion}} = (1 + e) a \]
• For the asteroid to cross Earth’s orbit, we must have
  \[ D_{\text{perihelion}} < 1.0167 \text{ AU} \]
• This is the critical value because \( e = 0.0167 \) and \( a = 1 \text{ AU} \) for the Earth’s orbit
• Asteroids orbiting close to Mars, with \( a = 1.6 \), will cross Earth’s orbit if \( e > 0.4 \)

• Most Apollo Asteroids are 1-10 km in size
• The Apollo Asteroids are the most dangerous for life on Earth due to the possibility of catastrophic impacts
• A collision with Earth would devastate an area 100 km in diameter
• The explosion would be equivalent to 1,000,000 1-megaton nuclear bombs
• Large asteroids strike the Earth every few hundred thousand years
• We are currently aware of almost 2000 Apollo Asteroids
• Harvard maintains a list of all known Apollo Asteroids:
  
Apollo Asteroids

- Max Wolf discovered the first Apollo Asteroid in 1918
- There are probably 2,000 Apollo Asteroids larger than 1 km
- There are probably 100,000 Apollo Asteroids larger than a football field
- There are perhaps 70-80 million Apollo Asteroids larger than a house


Asteroid Impacts

- The 1908 Tunguska event in Siberia caused a 15 megaton explosion that flattened thousands of square miles
- Recent simulations suggest that this was the result of the air burst of a 60-meter asteroid about 5 miles over the surface of the Earth
- Small fragments of stone found in trees are similar to the compositions of stony meteorites
Pattern of tree devastation after the Tunguska explosion

Asteroid Impacts

• In 1990 a smaller explosion was detected over the Pacific.
• In 1972, a 1000-ton object skipped off the atmosphere over Wyoming - and was photographed by tourists.
• This would have caused a 10-kiloton explosion in Canada if it had hit the Earth.
• A 100-meter iron asteroid hit Arizona about 20,000 years ago, leaving the “Arizona Meteor Crater.”
• A 10-km asteroid probably struck Earth about 65 million years ago, wiping out the dinosaurs.
• This was a typical-size Apollo Asteroid.

Arizona Meteor Crater
Asteroids

- There have been some close calls recently:

<table>
<thead>
<tr>
<th>Name</th>
<th>Year</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002 NY40</td>
<td>2002</td>
<td>150,000 km</td>
</tr>
<tr>
<td>2003 DW10</td>
<td>2003</td>
<td>543,000 km</td>
</tr>
<tr>
<td>2003 HW10</td>
<td>2003</td>
<td>331,000 km</td>
</tr>
<tr>
<td>2003 SW130</td>
<td>2003</td>
<td>162,000 km</td>
</tr>
<tr>
<td>2003 SQ222</td>
<td>2003</td>
<td>84,555 km</td>
</tr>
</tbody>
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- This is because the objects are difficult to detect until they are very close to the Earth.
- Hence we may have little or no warning about a collision with a killer asteroid.

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Asteroids

- Catalog statistics:
  - We know of 26 asteroids larger than 200 km in diameter
  - We have discovered 99% of asteroids larger than 100 km in diameter
  - We have discovered about 50% of those with diameters between 10-100 km
  - We have discovered very few smaller ones - but there are probably more than 1,000,000 of them with diameters around 1 km

- There are gaps in the asteroid distribution due to gravitational interactions with Jupiter
- These “Kirkwood Gaps” are similar to the gaps observed in the rings of Saturn
- The strongest gap is the 2:1 resonance:
NEAR Mission to Eros

http://near.jhuapl.edu/
The NEAR mission allowed us to estimate the mass of Eros. The mass of asteroid Eros is estimated to be about $7 \times 10^{18}$ g. Its size is about 33 km x 13 km x 13 km. The volume is estimated to be about $3 \times 10^{14}$ cm$^3$. Using this information, we can compute the average density:

$$\rho_{\text{eros}} = \frac{M_{\text{eros}}}{V_{\text{eros}}} = \frac{7 \times 10^{18}}{3 \times 10^{14}} \text{g/cm}^3$$

We find that

$$\rho_{\text{eros}} = 2.5 \text{ g/cm}^3$$

The density of water is:

$$\rho_{\text{water}} = 1 \text{ g/cm}^3$$

The density of rock is:

$$\rho_{\text{rock}} = 2.4 \text{ g/cm}^3$$

Since the average density is about 2.5 g/cm$^3$, the composition of Eros mostly rocky (probably little or no ice). For fun, let's compute the surface gravity and escape velocity for Eros. The escape velocity from the surface of Eros into space is given by

$$v_{\text{esc}} = \left(\frac{2GM_{\text{eros}}}{R_{\text{eros}}}\right)^{1/2}$$

This yields roughly

$$v_{\text{esc}} = 6.8 \text{ m/sec} = 15 \text{ miles/hour}$$

Hence you could "run" off Eros into space!
Surface Gravity

- We can compute the surface acceleration on a planet or moon using Newton’s laws of motion and gravitation:

\[ F = mA = \frac{-GMm}{R^2} \]

- Solving for the surface acceleration \( A \) yields

\[ A = \frac{-GM}{R^2} \]

- We find that

\[ A_{\text{Eros}} = \frac{-GM}{R_{\text{Eros}}^2} = 0.001 \text{m/s}^2 \]

- Despite their low gravity, some asteroids have their own moons!

http://www.johnstonsarchive.net/astro/asteroidmoons.html

Surface Gravity

- Using values for the Earth, Moon, Mercury, and Jupiter, we obtain for the surface accelerations

\[ A_{\text{Earth}} = \frac{-GM_{\text{Earth}}}{R_{\text{Earth}}^2} = 9.8 \text{m/s}^2 \]

\[ A_{\text{Moon}} = \frac{-GM_{\text{Moon}}}{R_{\text{Moon}}^2} = 1.7 \text{m/s}^2 \]

\[ A_{\text{Mercury}} = \frac{-GM_{\text{Mercury}}}{R_{\text{Mercury}}^2} = 3.7 \text{m/s}^2 \]

\[ A_{\text{Jupiter}} = \frac{-GM_{\text{Jupiter}}}{R_{\text{Jupiter}}^2} = 0.001 \text{m/s}^2 \]

- The acceleration at the surface of Eros is 10,000 times smaller than at the Earth’s surface!!!
Dactyl (about 1.6 km across)

Flooded crater in Quebec
Comets

- The name “comet” is derived from the Greek word “kome,” which means “hair.”
- This is because of the hair-like “tail” that comets display when they travel through the inner solar system.
- Comets travel in highly elliptical orbits, with large semi-major axes.

Comets

- Comets shine by reflecting sunlight from the coma and tails.
- Their nuclei are mostly ice, which sublimes into a gas when the comet approaches the Sun – forming the coma and tails.
- The tail points away from the Sun due to the pressure from the solar wind of particles.
Comets
For example, the semi-major axis of Halley’s Comet is $a = 18$ AU and its eccentricity is $e = 0.967$.

Comets show extreme variation in their distance from the Sun during each orbit.

- The minimum and maximum distances from the Sun are given by
  
  $D_{\text{perihelion}} = (1 - e) a$
  
  $D_{\text{aphelion}} = (1 + e) a$

- For Halley’s Comet, we find that
  
  $D_{\text{perihelion}} = 0.587$ AU
  
  $D_{\text{aphelion}} = 35.41$ AU

- The large variation in solar distance leads to extreme changes in the amount of solar heating experienced by the comet.

Comets
Using Kepler’s third law, which relates the semi-major axis $a$ to the orbital period $P$, we have

$$\left(\frac{P}{\text{years}}\right)^2 = \left(\frac{a}{\text{AU}}\right)^3$$

- Solving for the period $P$ yields

$$\frac{P}{\text{years}} = \left(\frac{a}{\text{AU}}\right)^{\frac{3}{2}}$$

- Since $a = 18$ AU for Halley’s Comet, we obtain $P = 76$ Earth years.

- This is a relatively short period for a comet.
Comets

Kepler’s second law (equal areas in equal times) implies that comets move very quickly when near the Sun, and slowly when far away. Hence, Comets spend most of their time moving very slowly, far from the Sun.

In 1708, Edmund Halley predicted a reappearance of a bright comet in 1758, after a previous visit in 1682. The comet reappeared as predicted in 1758, making Halley famous! (unfortunately, Halley was dead by then) Once the period of 76 years was known, historical records were searched to check for previous visits.
Comets

The records showed that Halley's Comet has been observed at every passage since 240 BC.

Short-Period Comets originate in the Kuiper Belt and have periods less than 200 years (e.g., Halley's Comet).

Kuiper Belt
Neptune's orbit

Comets

Long-Period Comets remain as icy, inactive cometary nuclei in the Oort Cloud until being perturbed by a passing star or suffering a close encounter with another cometary nucleus.

These comets have periods of $10^5 - 10^7$ years.

Oort Cloud
Neptun's orbit
Pluto's orbit
Comet's orbit

Nearest star

60,000 A.U.
The New Horizons Mission will investigate the Kuiper belt and beyond... 
http://pluto.jhuapl.edu/
• The objects in the Oort Cloud seem to have formed between Mars and Saturn, and were then flung much farther out due to gravitational interactions with the giant planets.
• Long-period comets are Oort Cloud objects that have interacted with another body, causing them to “fall” into the inner solar system.
• The objects in the Kuiper Belt were probably formed in their current locations.
• Short-period comets are Kuiper belt objects that have interacted with another body, causing them to “fall” into the inner solar system.
Comet Hale-Bopp, March 14, 1997

ion tail

dust tail
Comets

- The ion tail is straight, while the dust tail is slightly curved by the Sun’s gravity because the dust particles are more massive than the ions.
- Halley’s Comet was visited by the ESA’s Giotto spacecraft for the first time in history in 1986.
- The observations reveal that the nucleus has a mass of about $10^{16}$ g and is about 10 km in diameter.
Comets

- Spectroscopy indicates that the nucleus is composed of dust trapped inside methane, ammonia, and water ice
- This is the same primordial composition that we see in the moons of the outer planets
- The density of the nucleus is very low - only 0.1 g/cm³
- The nucleus is essentially a dirty snowball of primordial material
- As the comet sublimates, it breaks apart

Comets

- Eventually, a comet "dies" due to the breakup and sublimation of the icy "glue" that holds it together
- The remaining rock and dust can form swarms of meteors that follow the orbit of the original comet
- Some comets die by plunging into the Sun
Meteorites follow the orbit of the parent comet.

- When these meteors fall through Earth's atmosphere, they burn up, creating spectacular "shooting stars".
- The objects that reach the ground are called meteorites.
- Meteorites come in two groups, made mainly of either stone (most common) or iron (much rarer).

Iron Meteorite  Basaltic Meteorite

Meteor with northern lights
**Meteorites**

- Provide material from the early solar system for study on Earth
- The large crystals in iron meteorites form the Widmanstätten pattern
- The size of the crystals allows us to estimate the cooling time and therefore the size of the parent object
- Such crystals do not occur naturally on Earth’s surface

The ices in a comet can melt in dramatic ways, producing jets and flares.

Comet Shoemaker-Levy 9 colliding with Jupiter.