**Debris in the Solar System**

**Comets**

- “Dirty snowballs”, a mixture of ices and dust, ejected from solar system when planets formed
- Mass mostly contained in a nucleus (solid dirty snowball) with km-sized diameter
- Coma, a cloud of $\text{H}_2\text{O}$, $\text{CO}_2$ and other gases vaporized from nucleus during close passage to Sun
- Hydrogen cloud, a huge but sparse neutral $\text{H}$ cloud
- Dust tail, 1–10 million km long, composed of dust driven off nucleus by escaping gases when close to Sun
- Ion tail, 100’s of millions of km long, composed of plasma, driven off by solar wind
- Most comets reside far outside the orbit of Pluto, but a few are occasionally perturbed into orbits that take them near the Sun; some are in elliptical orbits and reappear
- After a few hundred passages near the Sun, icy material is lost, leaving a dead comet which can be mistaken for an asteroid
Comets

History

- Records of comets exist at least to 1140 BC
- Brahe observed comet of 1577, proved they are extraterrestrial
- Halley: some comets are periodic (1531, 1607, 1682)
- Halley’s Comet: 2467 BC (?), 240 BC (China), 1066 (Bayeux Tapestry)
- Motivated Newton to develop gravity theory

Orbits

- Hyperbolic: pass Sun once, depart forever
- Elliptical: periodic
- Peri-/Aphelion: closest/farthest solar approach

Origin

- Short-period come from Kuiper Belt, 35,000 icy bodies larger than 100 km, 30-100 AU
- Long-period come from Oort comet cloud, \(~10^{12}\) comets, 30,000 AU–1 lt. yr.
- Most formed within inner solar system, then pushed outwards by repeated near encounters
Giotto
Comet Tempel 1

- Discovered April 3, 1867 by Ernst Wilhelm Leberecht Tempel of Marseilles, France.
- Recognized as periodic by Bruhns of Leipzig; $P = 5.68$ years.
- In 1881, the comet had a close encounter with Jupiter and its period changed to 6.5 years, and perihelion was increased from 1.8 AU to 2.1 AU.
- The comet was subsequently lost, due to close approaches with Jupiter in 1941 and 1953, among others.
- Presently, comet is in a 1:2 resonance with Jupiter, $P = 5.5$ years.
Tempel 1 and Deep Impact
Tempel 1 and Deep Impact
Tempel 1 and Deep Impact

Comet 9P/Tempel 1 • July 4-5, 2005
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, P. Feldman (Johns Hopkins University) and H. Weaver (Johns Hopkins University Applied Physics Laboratory)
Tempel 1 Findings

- It's a fluff ball, about 50/50 rock and water ice grains.
- Rock dust consists of silicate grains, like crushed gems, smaller than sand grains.
- Clays and carbonates also exist (seashells are made from these), which is unexpected because it is thought they need liquid water to form.
- This may indicate a more thorough mixing of primordial solar system matter, so that grains formed in liquid water near the Sun are mixed with icy material from out by Uranus and Neptune.

Lattimer, AST 301, Debris Lecture – p.9/56
Rosetta

Comet 67P/Churyumov-Gerasimenko
Rosetta
Rosetta
Rosetta
Asteroids

- Also called minor planets or planetoids, largely lying within the orbits of Mars and Jupiter (main asteroid belt).
- Objects lying outside Neptune are called trans-Neptunian objects, centaurs or Kuiper-Belt objects.
- The first asteroid to be discovered was Ceres on Jan 1, 1801.
- Total asteroid mass is about 4% of the Moon’s mass. Ceres is about 32% of this. The first 4 asteroids have 51% of the total.
- Can be roughly classified by spectral type:
  - C-type  carbonaceous, 75%
  - S-type  silicaceous, 17%
  - L-type  metallic, 8%
  These percentages do not reflect true proportions, but only observed proportions; some are easier to see than others.
- About a third of asteroids are members of families that have similar orbits. Probably they form as a result of collisions between asteroids. They last for about a billion years.
- Asteroids are slowly lost due to collisions with planets and to gravitational encounters that eject them from solar system.
- Trojan asteroids collect in Lagrangian points (stable gravitational minima) $60^\circ$ ahead of and behind Jupiter in its orbit. Similarly for Mars, Earth and Venus.
- Asteroids are given a number in order of their discovery and the discoverer or the IAU may name them.
Heat Sources

- Collisions and accretion
- Radioactivity
- Tides
- Exothermic chemical processes
- Electrical currents from intense early solar wind
- Lightning
- Friction
- Gravitational potential energy

In a solid object, the first heat source of importance is from accretion, but this is unlikely to have entirely melted bodies. Collisions could melt surface layers. In a large enough object, radioactivity could melt entire bodies.
## Major Radioactivities

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Decay Product</th>
<th>Half Life</th>
<th>Decay Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sm$^{147}$</td>
<td>Nd$^{143}$</td>
<td>106 Gyr</td>
<td>0.3</td>
</tr>
<tr>
<td>Rb$^{87}$</td>
<td>Sr$^{87}$</td>
<td>48.8 Gyr</td>
<td>56</td>
</tr>
<tr>
<td>Th$^{232}$</td>
<td>Pb$^{208}$</td>
<td>14.4 Gyr</td>
<td>1.5</td>
</tr>
<tr>
<td>U$^{238}$</td>
<td>Pb$^{206}$</td>
<td>4.47 Gyr</td>
<td>203</td>
</tr>
<tr>
<td>K$^{40}$</td>
<td>Ar$^{40}$</td>
<td>1.25 Gyr</td>
<td>0.2</td>
</tr>
<tr>
<td>U$^{235}$</td>
<td>Pb$^{207}$</td>
<td>0.70 Gyr</td>
<td></td>
</tr>
<tr>
<td>I$^{129}$</td>
<td>Xe$^{129}$</td>
<td>15.7 Myr</td>
<td></td>
</tr>
<tr>
<td>Hf$^{182}$</td>
<td>W$^{182}$</td>
<td>7.8 Myr</td>
<td></td>
</tr>
<tr>
<td>Pd$^{106}$</td>
<td>Ag$^{106}$</td>
<td>5.6 Myr</td>
<td></td>
</tr>
<tr>
<td>Mn$^{53}$</td>
<td>Cr$^{53}$</td>
<td>3.7 Myr</td>
<td></td>
</tr>
<tr>
<td>Fe$^{60}$</td>
<td>Ni$^{60}$</td>
<td>2.6 Myr</td>
<td>3.2</td>
</tr>
<tr>
<td>Al$^{26}$</td>
<td>Mg$^{26}$</td>
<td>717,000 yr</td>
<td>4.0</td>
</tr>
<tr>
<td>Cl$^{36}$</td>
<td>Ar$^{36}$</td>
<td>301,000 yr</td>
<td></td>
</tr>
<tr>
<td>Kr$^{81}$</td>
<td>Br$^{81}$</td>
<td>210,000 yr</td>
<td></td>
</tr>
<tr>
<td>C$^{14}$</td>
<td>N$^{14}$</td>
<td>5730 yr</td>
<td></td>
</tr>
<tr>
<td>H$^3$ (tritium)</td>
<td>He$^3$</td>
<td>12.43 yr</td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing radioactive decay](image)
Example

- Sample contains three minerals A, B, C
- Minerals have different chemical abundances and different Rb/Sr ratios
- When the rock solidified, the isotopic ratios of each mineral had equal values of Sr$^{87}$/Sr$^{86}$ as per line “Then”
- For each decay of Rb$^{87}$, a Sr$^{87}$ nucleus is produced, so the points move in a 45° northwesterly direction as time proceeds
- Today, the isotopic ratios of each mineral lie on the line “Now”
- The older the sample, the larger the angle $\theta$ becomes
- $\tan \theta = t/t_{1/2}$
- The angle $\theta$ is 45° after 1 half life when $t = t_{1/2}$
Radioactivity in our Lives

Radioactivity in nature has three components:
- **Primordial** from before the creation of the Earth
- **Cosmogenic** produced by cosmic rays
- **Artificial** due to human activity

<table>
<thead>
<tr>
<th>Source</th>
<th>Dose (USGS)</th>
<th>Dose (mrem/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inhaled (Mostly Radon)</td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>Other ingested</td>
<td></td>
<td>39</td>
</tr>
<tr>
<td>Terrestrial radiation</td>
<td></td>
<td>28</td>
</tr>
<tr>
<td>Cosmic radiation</td>
<td></td>
<td>27</td>
</tr>
<tr>
<td>Cosmogenic</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Artificial (medical)</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>Artificial (consumer products)</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Artificial (coal + nuclear)</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>355</strong></td>
</tr>
</tbody>
</table>

A rem measures the equivalent dose and is equal to the absorption of 100 erg per g of material times a quality factor that depends on the radiation.

- At an altitude of 1 mile, add 27 mrem to total
- On the Colorado Plateau, add 63 mrem to total
- Add 1 mrem for each 1000 miles traveled by jet
- Add 7 mrem if you live in a stone, brick or concrete building
- Add 1 mrem if you watch too much TV
Carbon Dating

- $^{14}C$ originally on the Earth has long since decayed
- Cosmic rays bombard nitrogen nuclei in atmosphere at a fairly steady rate and convert some of them to $^{14}C$
- Rate of production by cosmic rays balances rate of decay, building up a steady-state abundance of $^{14}C$
- The abundances of C isotopes: $^{12}C$ - 98.89%, $^{13}C$ - 1.11% and $^{14}C$ - 0.0000000010%
- $^{12}C/^{14}C = 1$ trillion:
  This is the ratio found in living tissue
- Dead tissue has loss of $^{14}C$ by radioactive decay:
  $C_{14}(t) = C_{14}(0)e^{-t/8266\text{yr}}$
Nuclear Hysteria and Irrational Fears

• Closing of nuclear accelerator at Brookhaven National Lab in 1997 due to small tritium leak – equivalent to amount used in an exit sign.
  • Loss of medical research accelerator use and user fees
  • Clean-up cost was millions of dollars
  • Tritium radiation levels were lower than federal standards (4 mrem/yr) and would have decayed before reaching groundwater anyway
  • Even if drunk, tritium is rapidly evacuated from the body on timescales much less than decay times.
  • Clean-up was forced by political pressure from several environmental and anti-lab groups.

• Continued reliance on coal (56%) rather than nuclear (18%) power
  \[ \text{CO}_2 \text{ emission:} \quad \text{Coal 2 billion tons/year, same as 300 million autos. Nuclear: 0.} \]
  \[ \text{Pollution:} \quad \text{Coal burning releases 64\% SO}_2, 26\% \text{nitrous oxides (contribute to ozone loss), 33\% mercury, plus arsenic, cadmium, chlorine, lead, titanium, etc.} \]
  \[ \text{Radiation:} \quad \text{Coal burning effectively emits about 100 times more radioactivity (as particulate U, Th, K, etc., in exhaust) than nuclear, per unit of power generated. In addition, most radioactivity from coal is vented permanently into atmosphere rather than isolated as a solid. Mining uranium actually decreases future radon exposure: 1 nuclear plant saves 200 lives/year this way.} \]
Radiation exposure: Living next to a nuclear plant or 1 year = 1/50 radiation of dental X-ray or transcontinental plane trip. Living next to a coal plant is much worse. It has never been shown that incremental exposure to radiation is harmful.

Energy equivalents: The energy content of nuclear fuel released in coal combustion is greater than the energy content of the coal consumed!

Mining accidents: 100/yr coal deaths in US, over 5000/yr worldwide; nuclear less than 10/yr worldwide.

Waste: Solid waste has much smaller volume; reprocessed wastes need be isolated for only 600 years until radiation levels fall below those of initial fuel, about 1% of its peak radioactivity.

Fuel costs: Coal is 3 to 4 times as expensive as nuclear fuel, and oil and natural gas are 4 times more expensive still. However, capital construction costs for nuclear plants are higher, mostly because of strict regulations. Overall, including construction and decommissioning costs, coal ends up being twice as expensive.

Accidents: Chernobyl-style events cannot occur in Western-designed plants. Chernobyl led to thyroid cancer in about 1000 children and several cancer-related deaths so far, but most of these could have been avoided due to lack of prompt response (i.e., making iodine tablets available) by the government. Three Mile Island accident has led to no provable cancers due to Western-designed containment.

Terrorism: In last 20 years, 1 million Africans have been killed by machete; car bombs kill thousands per year; firearms kill 30,000/yr in US; nuclear – 0 so far.
Risk

From TIME
Dec 4, 2006
Centers for Disease Control and Prevention

Terrified of bees, snakes and swimming pools?

Thousands of Americans die in accidents every year, but the odds are extremely high that you won’t be one of them. A look at what killed Americans in 2003, the most recent year for which data are available, shows that just 4% of fatalities were accidental. So go ahead and take that plane trip or swim in the ocean. Just be careful out there.

Selected causes:

- Motor vehicle accident: 44,757
- Drug overdose: 11,212
- Motorcycle accident: 3,676
- Falling down stairs: 3,004
- Choking on food: 875
- Bicycle accident: 762
- Falling out of bed: 594
- Pool drowning: 515
- Falling off a ladder: 365
- Bathtub drowning: 332
- Slipping on ice/snow: 103
- Bee/wasp sting: 66
- Lightning strike: 47
- Dog attack: 32
- Skydiving: 22
- Crushing by human stampede: 22
- Commercial airline accident: 22
- Playground-equipment accident: 3
- Snakebite: 2
- Marine-animal attack: 1

*Excluding motorcycles

**Number varies widely by year. The average number of annual fatalities for the past 10 years is 82, including the 265 people who died on airplanes on Sept. 11, 2001

called the "9/11 effect." It produced a third again as many fatalities as the terrorist attacks.

Maybe you should worry more about your heart

Even if you exercise regularly and don’t smoke or drink, you will probably die of a disease. Two ailments—heart disease and cancer—cause half of all deaths in the U.S. Exotic bugs like avian flu and mad cow disease might grab a lot of headlines, but so far they haven’t killed a single person in the U.S.
Why Risk Assessment is Difficult

The Dread Factor
Humans don’t treat all death as being created equal. Fear is increased with pain and suffering potential. This leads to “probability neglect”. A slight increase in cancer rate compared to automobile crashes; AIDS compared to heart disease. We also dread catastrophic risks: e.g., terrorism vs. climate change.

Unfamiliar Risks
Unfamiliar risks are scarier than familiar ones. But repeated events lead to “habituation”, which lessens the response.

The Illusion of Control
Driving vs. flying. The so-called 9/11 effect: 1000 more highway fatalities occurred between October and December 2001 than the year before, 30% more fatalities than occurred on 9/11 itself.

Risk that Confers Pleasure
Drinking, risky sex, recreational drugs, cigarettes, ice cream.

Flawed Comparisons
Specificity: Prefer “saving 98% of 150 people” compared to “saving 150 people”. Greater risk from “drowning in bathtub” than “mad cow disease”: true, but comparing apples and oranges. Preventing 1% risk of terrorist attack in US (with <1000 casualties) was used to justify a war in Iraq that had 100% chance of tens of thousands of casualties.
Evidence for Al\textsuperscript{26}

- A tight correlation of Al concentrations in minerals with the decay product Mg\textsuperscript{26}.
- Al\textsuperscript{26} was present when meteorites formed; signature of a nearby supernova.
Al$^{26}$ in the Galaxy

- The amount of Al$^{26}$ implies a gravitational collapse supernova rate of about 2 per century in the Galaxy. Most must occur in inner galaxy and remain invisible to us, obscured by dust and gas.
$Al^{26}$ in the Galaxy

- Signature of galactic rotation through Doppler shifts.
Radioactive Heating

- The energy released per radioactive decay is $\epsilon$
- The mean life of a radioactive nucleus is $\tau$
- The initial fraction of the number of atoms that are radioactive is $Y$
- The total number of atoms in an asteroid is $N$
- The total mass of an asteroid is $M$

$$M = \frac{4\pi}{3} \rho R^3 = N \frac{\mu}{N_o}$$

- The mean molecular weight is $\mu$; the internal energy is $3Nk_B T/2$
- The heating rate of an asteroid is $NY \frac{\epsilon}{\tau} e^{-t/\tau}$
- The cooling rate of an asteroid is $4\pi R^2 \sigma T^4$

$$\frac{dE}{dt} = \frac{3}{2} Nk_B \frac{dT}{dt} = NY \frac{\epsilon}{\tau} e^{-t/\tau} - 4\pi R^2 \sigma T^4$$

- The maximum temperature is reached when $dT/dt = 0$ (for Al$^{26}$):

$$T_{max} = \left( \frac{NY \epsilon e^{-t_{max}/\tau}}{4\pi R^2 \sigma \tau} \right)^{1/4} \sim \left( \frac{N_o Y \epsilon \rho R}{\mu \tau \sigma} \right)^{1/4} \sim 1000 \left( \frac{R}{\text{km}} \right)^{1/4} \text{ K}$$
What is a Kuiper-Belt Object?

The Kuiper Belt is a disk-shaped region past the orbit of Neptune extending roughly from 30 to 50 AU from the Sun, containing many small icy bodies. It is now considered to be the source of the short-period comets. About 1000 are known, and many (like Pluto) are in a 3:2 orbital resonance with Neptune.

Centaur objects, of which 9 are known, orbit between Jupiter and Neptune. Their orbits are unstable, and are probably displaced from the Kuiper Belt.
### Kuiper Belt Objects

<table>
<thead>
<tr>
<th>Name</th>
<th>Diameter (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003 UB313</td>
<td>2400 ± 100</td>
</tr>
<tr>
<td>Pluto</td>
<td>2320</td>
</tr>
<tr>
<td>2003 EL61</td>
<td>1200?</td>
</tr>
<tr>
<td>2005 FY9</td>
<td>1250?</td>
</tr>
<tr>
<td>Charon</td>
<td>1270</td>
</tr>
<tr>
<td>Sedna</td>
<td>&lt; 1500?</td>
</tr>
<tr>
<td>2004 DW</td>
<td>~ 1500</td>
</tr>
<tr>
<td>Quaoar</td>
<td>1200 ± 200</td>
</tr>
<tr>
<td>Ixion</td>
<td>1065 ± 165</td>
</tr>
<tr>
<td>2002 AW197</td>
<td>890 ± 120</td>
</tr>
<tr>
<td>Varuna</td>
<td>900 ± 140</td>
</tr>
</tbody>
</table>
They Have Moons!
What are Near-Earth Objects?

- Comets and asteroids deflected into orbits with perihelion distance \( q < 1.3 \) AU
- Made of water ice plus embedded dust
- Originated in cold outer solar system
- Primordial, leftover building blocks of planets
- Classes of Near-Earth Asteroids:
  - Atens - Earth-crossing, semi-major axis \( a < 1.0 \) AU
  - Apollos - Earth-crossing, \( a > 1.0 \) AU
  - Amors - Earth-approaching but interior to Mars, \( a > 1.0 \) AU and \( 1 \) AU < \( q < 1.3 \) AU,
  - PHAs - Potentially Hazardous Asteroids
    - Closest approach to Earth less than 0.05 AU
    - Absolute magnitude less than 22.0
    - Assuming albedo is 13%, this means diameter greater than 150 m (500 ft)
    - There are currently 773 known PHAs
How Do We Find Near-Earth Objects?

- Early efforts relied on comparison photographs taken several minutes apart
- Vast majority of objects recorded were stars and galaxies, which don’t move
- Special stereo viewing microscopes pick out NEOs
- Current efforts use CCD cameras
- Computer-aided comparisons of digital images
- NASA’s goal: Find $> 90\%$ of NEAs $> 1$ km within 10 years
- Total population estimated to be about 1000
  - Lincoln Near-Earth Asteroid Research (LINEAR)
  - Near-Earth Asteroid Tracking (NEAT)
  - Spacewatch
  - Lowell Observatory Near-Earth Object Search (LONEOS)
  - Catalina Sky Survey
  - Japanese Spaceguard Association (JSGA)
  - Asiago DLR Asteroid Survey (ADAS)
Impact Hazard

- Torino Scale: measures relative risks. Rating of 0 indicates no likely consequences; 1 object merits careful monitoring.
- Palermo Scale: measures relative risk $R$.

$$PS = \log_{10} R$$

$$R = \frac{P_{Impact}}{f_B DT}$$

$$f_B = 0.03E^{4/5}$$

is annual probability of an impact event with energy $E$ in MT at least as large as the event in question.
$DT$ is the time until potential impact in years.

- Two top risks at present are
  - 2007 VK184 (2048-2057) with 4 potential impacts, diameter 0.13 km, PS=-1.82, TS=1
  - 99942 Apophis or 2004 MN4 (2036-2069) with 3 potential impacts, diameter 0.27 km, PS=-2.41, TS=0
  - 2004 XY130 (2009-2107) with 87 potential impacts, diameter=0.503 km, PS=-2.73, TS=0
Studying Near-Earth Objects in Space

• Typical instruments:
  • Imager: Camcorder
  • IR and UV spectrometers to infer mineralogical and gaseous compositions
  • Lidar: Optical equivalent of radar, useful to define shape of target and aids in navigation
  • X-ray, $\gamma$-ray and $\alpha$-ray spectrometers to infer chemical/elemental composition of surface. X-rays come from Sun, $\gamma$-rays from cosmic rays, $\alpha$-particles from a spacecraft Curium source
  • Dust mass spectrometer detects high-velocity dust whose impacts produce ions
  • Magnetometer to infer magnetic field of target
  • Package to measure temperatures/densities of plasma clouds created as sun’s radiation ionizes cometary atmosphere. Also used to monitor DS1 spacecraft ion engine drive
**Spacecraft Missions**

- **Near-Earth Asteroid Rendezvous (NEAR)** 2/17/96 - 2/12/01
  - Flyby of 243 Mathilde and 433 Eros, touchdown on 433 Eros

- **Deep Impact** 11/1/99 - 7/4/05
  - Study and excavate a crater on Comet Tempel 1

- **Deep Space 1 (DS1)** 10/25/98 - 9/22/01
  - Flyby of 9969 Braille and Comet Borrelly
  - Tested new technology – ion drive rocket, concentrating solar panel, auto navigation system using asteroids
Spacecraft Missions

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  • Flyby of 243 Mathilde and 433 Eros, touchdown on 433 Eros

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  • Study and excavate a crater on comet Tempel 1
  • Flyby of comet Hartley 2

• Deep Space 1 (DS1) 10/25/98 - 9/22/01
  • Flyby of 9969 Braille and comet Borrelly
  • New technologies – ion drive, concentrating solar panel, asteroid navigation system

• Stardust 2/7/99 - 3/25/11
  • 2 interstellar dust collections, flyby of 5535 Annefrank, encounter with comet Wild 2
  • Discovery of olivine and other minerals containing Ca, Al and Ti, all hi-T condensates, in comet dust
  • Reconfigured to encounter comet Tempel I, 2/14/11
Stardust Results

- Dust particles found are up to a million times larger than typical stardust grains.
- It had been expected that individual grain would be about 1/3 micrometer in diameter.
- In addition, stardust formed a very minor component of material. It is identified by anomalous isotopic composition compared to solar system.
- Silicate crystals identified, which are not found in interstellar dust. They did not form by mild heating of interstellar dust: they are too large and appeared to have been formed at temperatures in excess of 1300 C.
- Further supports finding from Tempel 1 that material from hot inner regions of solar system were mixed out to the orbit of Neptune where the comets formed.
- One of the most spectacular particles found is a Calcium Aluminum Inclusion, a high temperature condensate, one of the first solids to condense in the solar nebula.
- Some organic material is unlike anything seen before in extraterrestrial materials (like meteorites), being more primitive. The PAH’s found were very rich in O and N and are very volatile.
Findings Concerning Comet Hartley-2

- A pebbly trail discovered by WISE = Wide-field Infrared Survey Explorer
- Deep Impact found its core does not have a uniform composition: jets spewing ice and CO\textsubscript{2} in one direction, and others spewing water vapor but no CO\textsubscript{2}.
- Deep Impact also found three types of ices: water ice containing methanol, CO\textsubscript{2} ice, and ethane ice.
More Spacecraft Missions

- Hayabusa 5/9/03 - 9/12/05
  - landing on 25143 Itokawa (diameter = 600 m), planned sample return to Earth in summer 2007
  - Suffered fuel leak after successful second landing, prevents communications to direct rocket’s return

- Dawn
  - Investigate in detail Ceres and Vesta

- Rosetta 3/2/04 - 2015
  - ESA probe to Comet 67 Churyumov-Gerasimenko, utilizing 3 Earth and 1 Mars gravity assist mvr
  - To orbit comet toward its perihelion for 17 months
  - Includes lander named Philae, island in River Nile containing obelisk with bilingual inscriptions providing Champollion with final clues needed to decipher hieroglyphs of Rosetta Stone
  - Flyby 2867 Steins (5/9/08), 21 Lutetia (7/10/2010)
**Dawn at Vesta**

- A mountain in the south polar region 3 times higher than Mt. Everest.
- Equatorial troughs consistent with models of fractures due to giant impact.
- Diverse composition, particularly around craters.
Asteroids Visited by Spacecraft

- 21 Lutetia
- 253 Mathilde
- 243 Ida
- 243 Ida 1 Dactyl
- 433 Eros
- 951 Gaspra
- 2867 Šteins
- 4 Vesta
- 25143 Itokawa
Meteorites

Types

There have been about 1050 observed falls and about 31,000 finds.

- Stony meteorites
  - Chondrites (85.7% of falls, 52% of finds) oldest, 4.55 Byrs old.
    - Ordinary contain both volatile and oxidized elements, formed in inner belt, and are the most common type.
    - Carbonaceous contain more volatiles, formed in outer belt.
    - Enstatite contain more refractory elements, formed in the inner SS.
  - Achondrites (7.1% of falls, 1% of finds) show evidence of igneous processes.
    - HED group
    - SNC group (Martian)
    - Aubrites
    - Ureilites
    - Eucrites (Vesta)
- Stony iron (1.5% of falls, 5% of finds)
  - Pallasites
  - Mesosiderites
- Iron (5.7% of falls, 42% of finds) formed in meteorite parent body cores.
Meteorites are

- **primitive**: unaltered (mostly chondrites, esp. carbonaceous chondrites)
- **differentiated**: evolved, products of melting, separation

Interesting discoveries:

- Organic compounds in carbonaceous chondrites (Allende, Murchison) are equally left- and right-handed
- Isotopic anomalies in carbonaceous chondrites: $^{16,17,18}$O, $^{26}$Mg (from $^{26}$Al, halflife 720,000 yrs)
- SNC meteorites traced to Mars
- Possible microfossils, complex hydrocarbons, biominerals in SNC meteorite ALH 84001
- Eucrites traced to Vesta
- Sayh al Uhaymir 169 is a meteorite from the Moon
- The meteorite Kaiduri is possibly from Mars’ moon Phobos

On September 15 2007 a chondritic meteorite hit near Carancas, Peru and poisoned about 30 villagers that approached the impact site (600 more had provoked psychosomatic ailments). The impact caused boiling of arsenic-contaminated groundwater from natural deposits. The local province is turning this into a tourist attraction.
Tidal Forces

\[
F_t = \frac{GMm}{(R - r)^2} - \frac{GMm}{(R + r)^2}
\]

\[
= GMm\left[\frac{(R + r)^2 - (R - r)^2}{(R - r)^2(R + r)^2}\right]
\]

\[
\approx GMm\frac{4Rr}{R^4} = GMm\frac{4r}{R^3}.
\]

Tides generate a tidal bulge along the equator. As the object rotates, the bulge is dragged around the object opposite to the spin. The pushing and pulling of the planetary material generates frictional heat and produces a torque (a force that changes angular momentum). The strong tides have synchronized, or tidally locked, the rotation of the Moon with its orbital period, 28 Earth days. Tides are pushing the Moon away.
Effects of Tidal Forces

- Tides or tidal bulges: changing sea levels
- Resonances: rotations and orbits of bodies become synchronized in integer ratios
  - Mercury in a 3:2 rotation:orbit resonance
  - Moon locked to Earth; a 1:1 rotation:orbit resonance
  - Venus and Earth in a 13:8 orbital resonance
  - Phobos & Deimos locked to Mars
  - Io, Europa, Ganymede, Callisto and 4 others locked to Jupiter
  - Mimam, Enceladus, Tethys, Dione, Rhea, Titan, Iapetus and 8 others locked to Saturn
  - Miranda, Ariel, Umbriel and Titania locked to Uranus
  - Proteus and Titania locked to Neptune
  - Charon and Pluto locked to each other; Nix & Hydra in 1:4 and 1:6 resonances
  - Pluto and many Kuiper Belt Objects in a 3:2 orbital resonance with Neptune
  - Tau Bootis locked to an orbiting giant planet
  - Gliese 581 b and c are locked to parent star Gliese 581
- Tidal heating: Satellites rotate at a constant speed, but in an eccentric orbit the orbital speed varies with separation (Kepler’s 2nd Law). The tidal bulge is pulled back and forth; the friction heats the interior.
  - An extreme case is the Io, Europa and Ganymede system in a 4:2:1 orbital resonance that makes Io tremendously volcanically active and maintains a liquid shell under Europa’s icy crust.
• Roche limit: Minimum distance from a planet that a solid satellite can orbit without tides pulling it asunder. 
Equate tidal force and self-gravity of 2 moonlets of mass \( m \) and radius \( r \):

\[
GMm \frac{4r}{R_R^3} = G \frac{m^2}{4r^2}, \quad \text{or} \quad R_R = 2^{4/3} r \left( \frac{M}{m} \right)^{1/3}.
\]

Planet's average density is \( \rho_{\oplus} = \frac{3M_{\oplus}}{(4\pi R_{\oplus}^3)} \)
moon's average density is \( \rho_m = \frac{3m}{(4\pi r^3)} \)

Implies that the Roche limit is

\[
R_R = 2^{4/3} \left( \frac{\rho_{\oplus}}{\rho_m} \right)^{1/3} R_{\oplus} \approx 2.5 - 3R_{\oplus}.
\]

• Rings and satellites: Large satellites must orbit outside the Roche Limit. Rings can extend to the Roche Limit.
  • All the Jovian planets have rings; Outer edge of Saturn’s A ring is at \( 2.3R_{\oplus} \)
• Eventual loss of prograde satellites: Frictional loss of angular momentum leads to expanding orbits.
• Destruction of retrograde satellites: Retrograde satellites have shrinking or decaying orbits and will eventually fall within the Roche Limit and be destroyed.
  • Triton will be destroyed in 100 Myr to 1 Gyr.