Last time: Icy Moons of the Outer Solar System
- Captured moons vs. primordial moons: orbits and sizes
- Surface modification processes
- Jupiter’s moons - systematics (volcanic/rocky - cold and icy)
- Saturn’s Large Satellites, and Titan
- Moons of Uranus and Neptune

Today: Kuiper Belt objects, asteroids, and meteorites
- Pluto and Kuiper Belt objects
- Asteroids: location, sizes, and compositional families
- Meteorites: irons, stones, stony irons
  - correlation between meteorites and asteroid families
  - some show no evidence of heat processing

Pluto - and beyond
- Discovered in 1930 in search for trans-Neptunian planet
- Extremely small
  - $M = 0.002 \, M_{\text{Earth}} \ (1/6 \, M_{\text{Moon}})$
- Extremely remote
  - orbital period = 248 years
  - eccentric orbit - was closer than Neptune from 1979 through 1999!
- Has a large moon (and several smaller ones)
  - Charon discovered in 1978
  - observed by HST
Pluto

Water ice mountains floating in a sea of soft nitrogen ice
Pluto is not alone out there

- Pluto is one of many “trans-neptunian objects” (TNOs)
- a.k.a. **Kuiper Belt objects (KBOs)**
- 1st KBO found in 1992, Quaoar found in 2002
- ERIS - found in 2005 is 25% bigger than Pluto
Asteroids

swarm of small bodies orbiting (mostly) between Mars & Jupiter

- **Numbers**
  - over 8,000 orbits known
  - brightest still invisible to unaided eye
  - largest = Ceres: 1000km diameter
  - a few dozen bigger than 100 km
  - common size: 10-20 km
  - countless more of smaller size

- **The Main “Asteroid Belt”**
  - semi-major axes between 2.1 and 3.3 a.u.
  - average = 2.81 - very close to Bode prediction!
  - total mass << Mass of our Moon

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### The Case of the missing planet

Bode’s law (1772) “predicts” semi-major axes

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### Asteroid Groups:

- main belt
- Trojans @ “Lagrangian Points”
- Earth-crossers
- Hidalgo - beyond Jupiter
- Chiron - beyond Saturn
1 Ceres
by DAWN, May 2015

950 km

4 Vesta
by DAWN, July 2011

560 km

Gaspara

Mathilde

Phobos

Ida

Deimos

Types of Asteroids

- C-type (common in outer asteroid belt)
  - extremely dark - low reflectivity
  - 75% of all asteroids
  - no evidence of high mineral content
  - carbon rich

- S-type (silicates - inner belt)
  - spectral evidence for olivine - a silicate mineral

- M-type (rare)
  - metallic iron/nickel

Asteroid origins:

- total mass much less than a small planet
- some evidence of differentiation
- ???
**Earth-Crossing Asteroids**

~ 1000 objects whose orbits cross 1 a.u.

- **Aten asteroids:**
  - perihelion inside 1 a.u.
  - aphelion beyond 1 a.u.
  - nearly circular orbits
  - about 100 known

- **Apollo asteroids**
  - very elliptical orbits
  - perihelion well inside 1 a.u.
  - aphelion well beyond 1 a.u.
  - all < 8km across

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**Orbits of potentially hazardous asteroids**

- **2002 NY40**
  - August 2002
  - Fick Observatory
  - Duration: 90 seconds!
**Asteroids on Earth: Meteors and Meteorites**

- **Meteorite**
  - tiny body (<1 cm to ~10 m) entering atmosphere
  - nearly all burn up completely - comet dust?
  - fragment(s) that survive to ground
- **Meteor** - a “shooting star”
  - flash of light as meteoroid burns up
  - 80-90 km high at brightest
- **average meteor rate** - about 7/hr (in a dark sky)
- **BUT: METEOR SHOWERS:**
  - occur when Earth passes through orbit of a comet
  - annual events - up to 60 or more per hour
  - mostly small particles, but still bright meteors
  - appear to radiate from a point in sky: “radiant”
  - i.e. Leonids - Nov 17
Types of Meteorites

primitive or processed, they are all older than dirt

• Stony meteorites (94% of all falls)
  - ordinary chondrites (~80%)
    - chondrules - silicate balls
    - other inclusions - Al, Mg, S
  - achondrites (~10%)
    - stones with no inclusions
  - carbonaceous chondrites (~ 4 %)
    - carbon-rich inclusions
    - complex organic molecules (amino acids)
    - water-rich chondrules - never melted!

• Iron meteorites (5% of all falls)
  - nearly pure iron/nickel alloy
  - large crystals - very slow cooling

• Stony- Iron meteorites (1% of all falls)
  - mixture of iron and silicates

Meteorites and Asteroids

- Irons (M-type asteroids):
  - ages of 4.6 Gyr - among oldest objects known
  - clear evidence of melting, and slow cooling
  - remnant of a differentiated protoplanetary core
  - size of body > 100 km

- Ordinary chondrites: (S-type asteroids)
  - also 4.6 Gyr old
  - matrix and chondrules - once molten
  - possible crust/mantle of parent body
  - others maybe from never-differentiated bodies

- Carbonaceous chondrites: (C-type asteroids)
  - some inclusions possibly older than 4.6 Gyr
  - water-rich minerals, fragile carbon compounds never melted!
  - pristine material out of which planets formed?

most are leftovers from formation of the planets