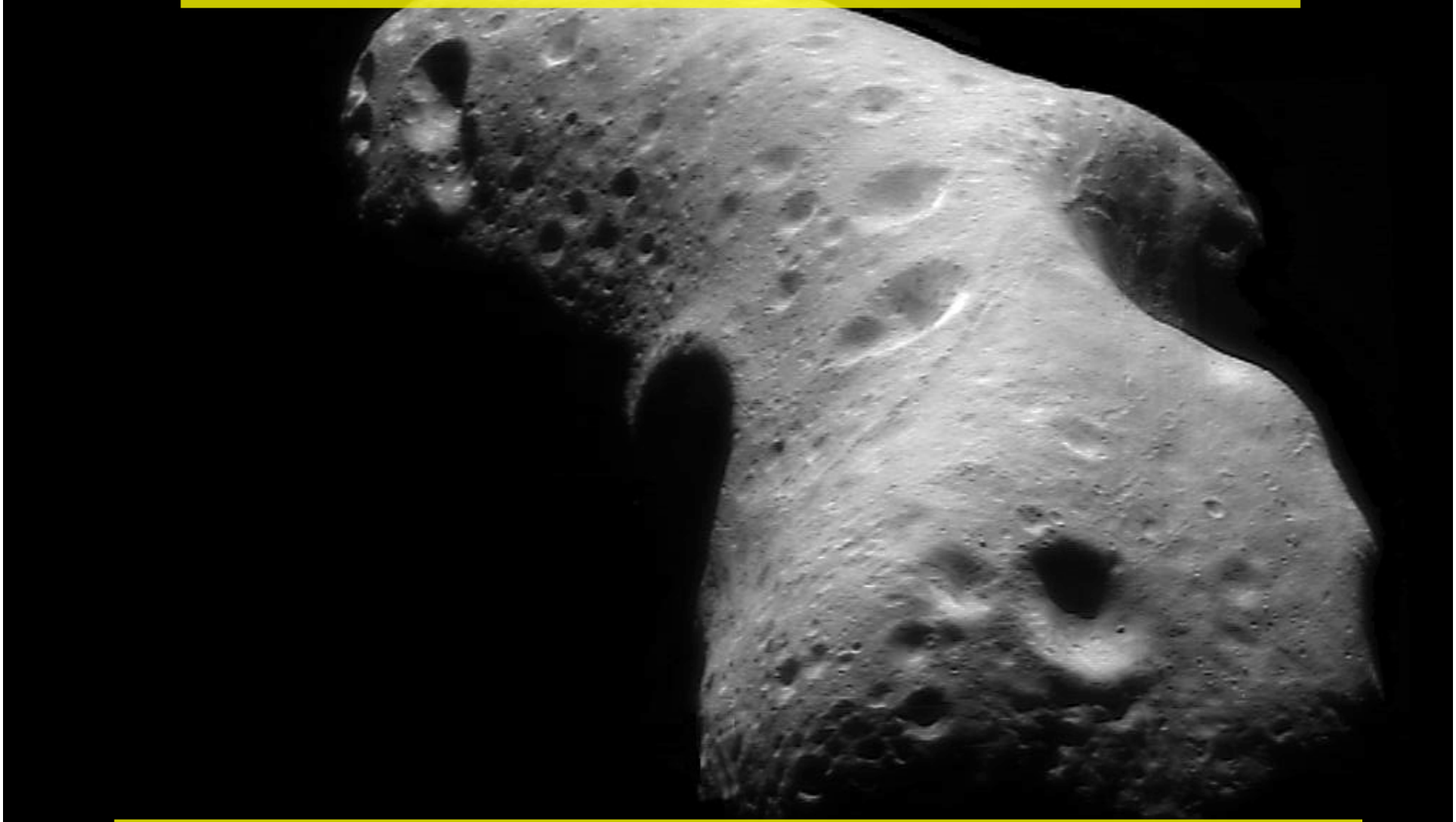
- **Announcements**
  - **HW4 available today**
    - **You have two weeks for this one**
  - **First lecture after Spring Break – special topic**
    - **Several options to choose from…**
    - **Global warming**
    - **The space race**
    - **Mass extinctions on Earth and Impacts**

Asteroids and Meteorites

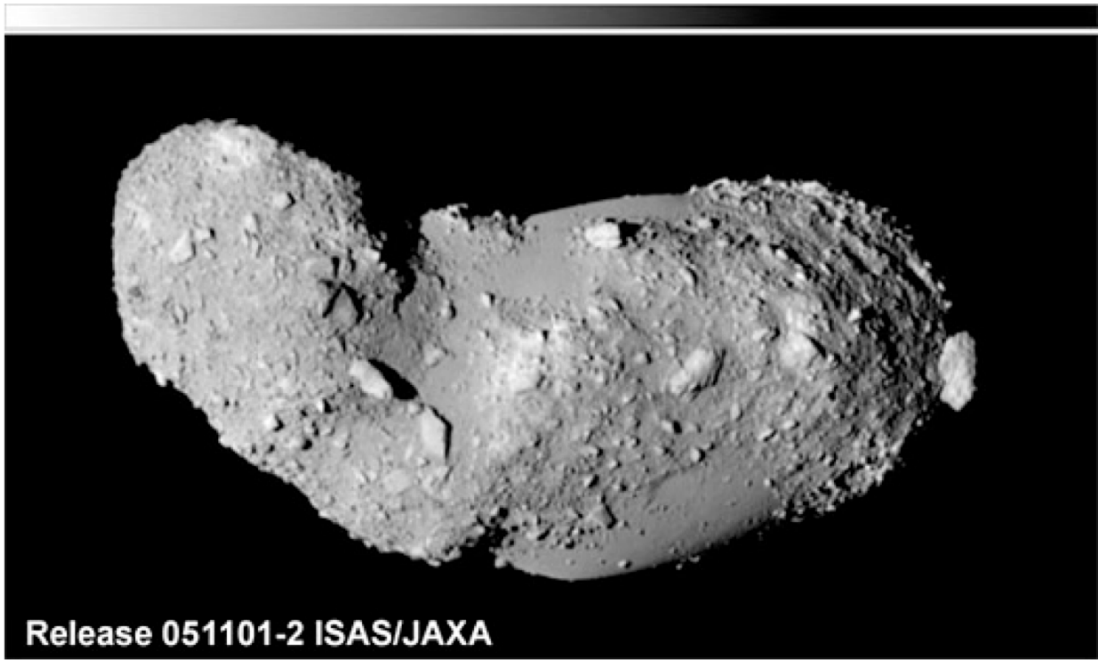


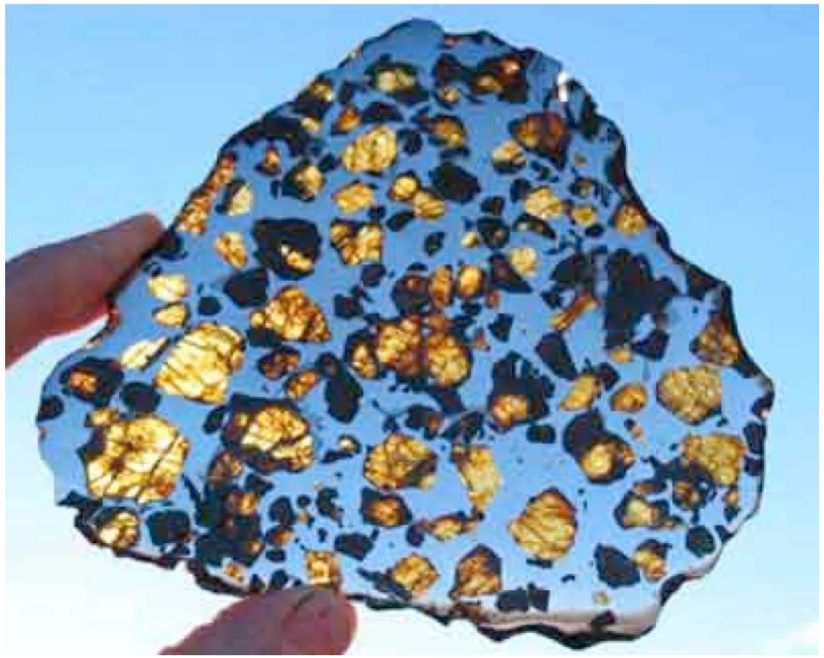
PTYS/ASTR 206 – The Golden Age of Planetary Exploration

Shane Byrne – shane@lpl.arizona.edu

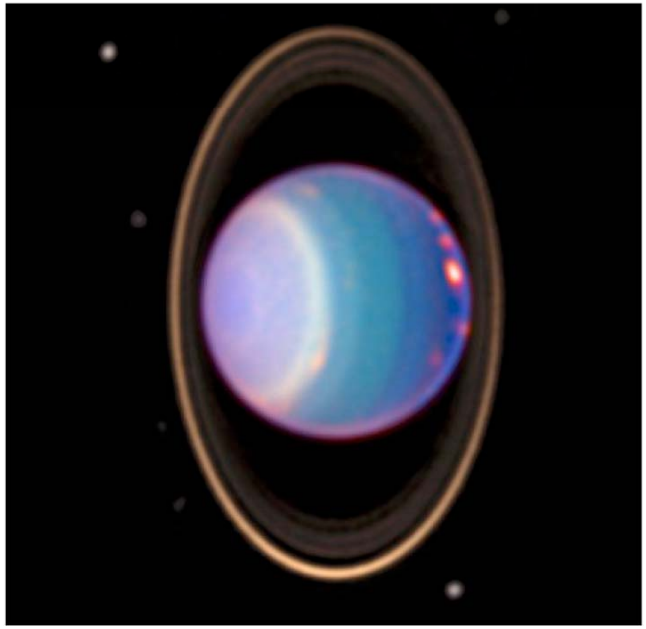
In this lecture…

- Discovery of Asteroids
  - A missing planet?
- The main asteroid belt
  - Where did it come from?
  - The Kirkwood gaps
  - Trojans
- Properties of Asteroids
  - Shapes, sizes, compositions
  - Rubble piles?
- Near-Earth asteroids
  - Where do they come from?
  - How dangerous are they?
- Meteorites
  - Different types and what they tell us
  - Meteor showers

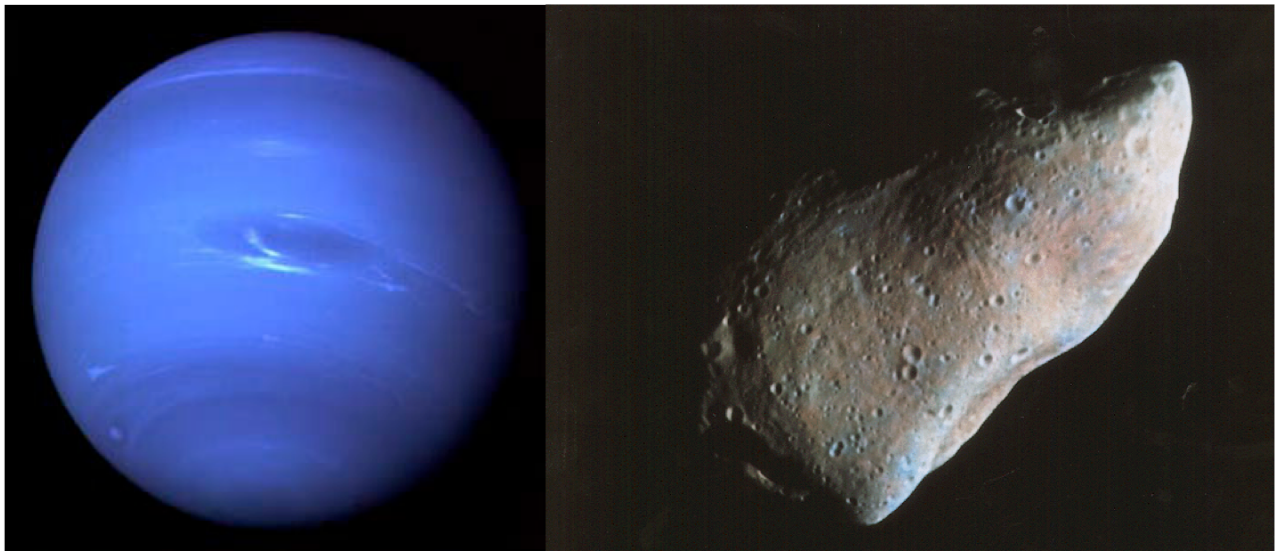




Discovery of asteroids



- The solar system in 1800…
  - Mercury, Venus, Mars, Jupiter Saturn
    - known from antiquity
  - Uranus recently discovered
    - With telescopes in 1781
  - Neptune not yet discovered
  - Pluto and the Kuiper Belt not yet discovered
  - Asteroids not yet discovered

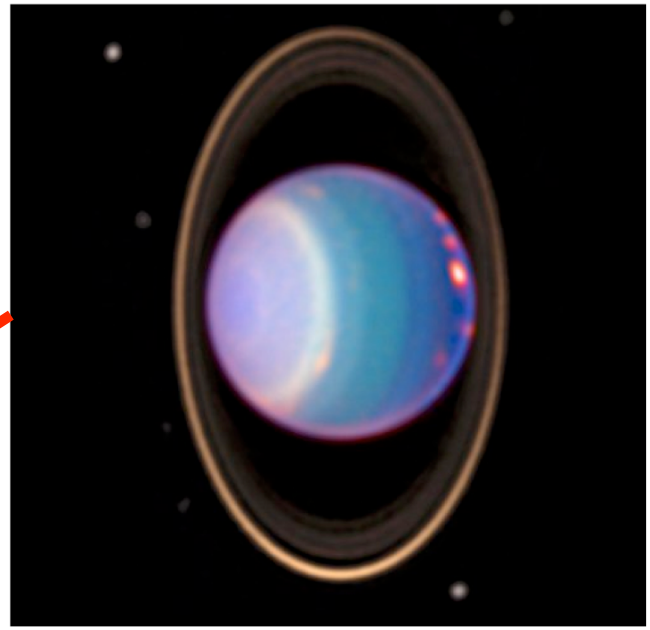


- **Titus-Bode law**
  - **Mid 1760s**
  - **A mathematical sequence that seemed to predict the sizes of the planets' orbits**

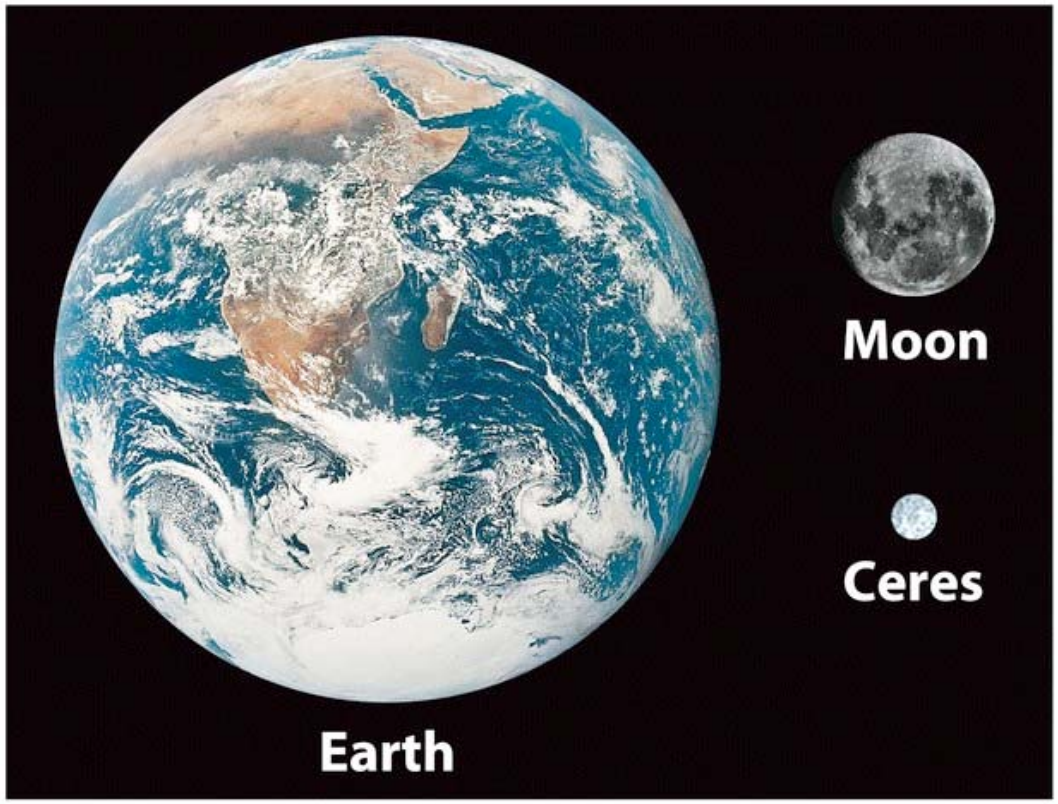
Start with	0	1	2	4	8	16	32	64	128
Multiply by 0.3	0	0.3	0.6	1.2	2.4	4.8	9.6	19.2	38.4
Add 0.4	0.4	0.7	1.0	1.6	2.8	5.2	10	19.6	38.8

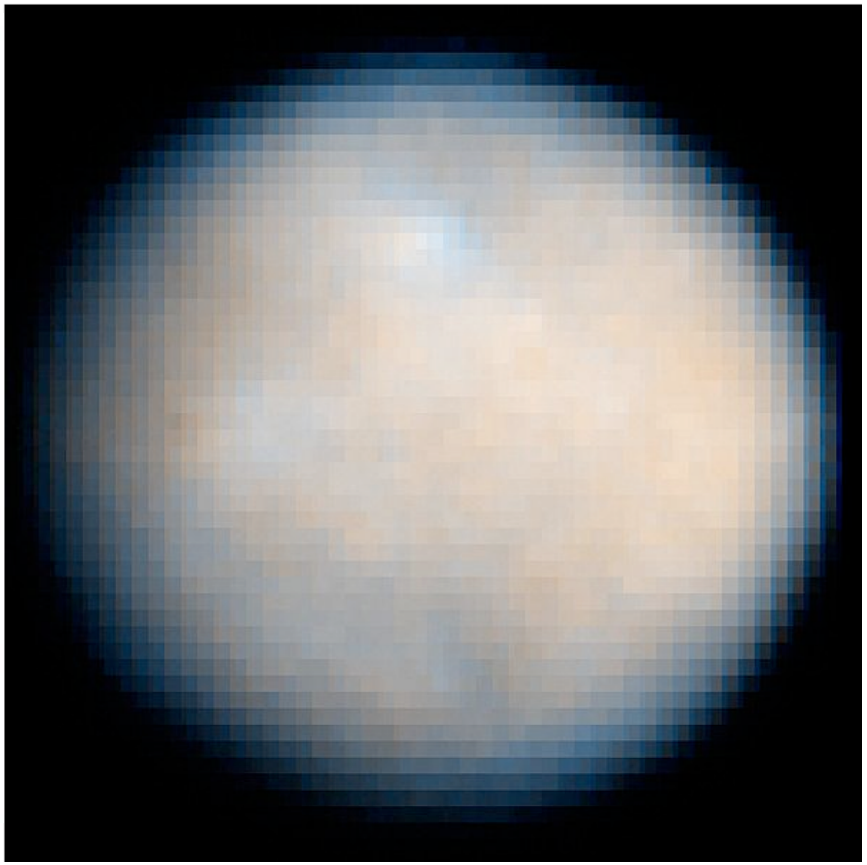
- **These numbers are similar to the sizes of the planets' orbits in AU**
  - **Uranus was discovered ~15 years later and fit right into this scheme**
  - **Had something been missed between Mars and Jupiter?**

Planet	Titus-Bode	Observation
Mercury	0.4	0.39
Venus	0.7	0.72
Earth	1.0	1.0
Mars	1.6	1.52
-	**2.8**	-
Jupiter	5.2	5.2
Saturn	10	9.5
Uranus	19.6	19.2
-	**38.8**	-



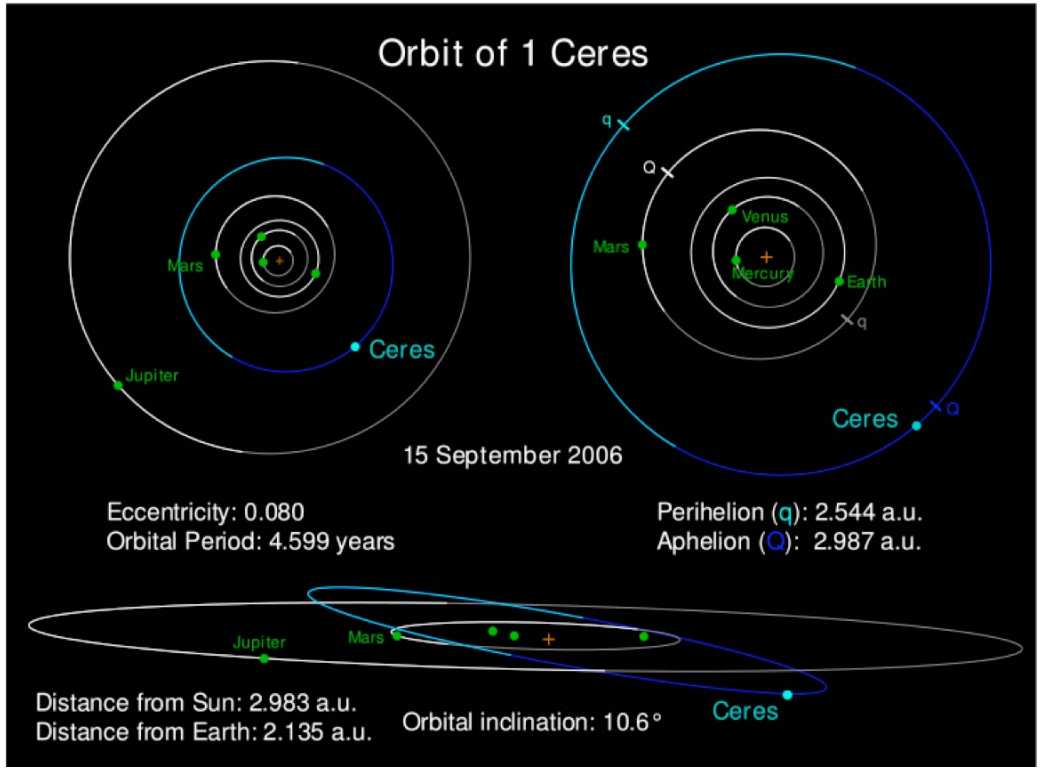
- **Astronomers searched with telescopes for this ‘missing planet’.**
  - **In 1801 a planetary object was found**
  - **Giuseppe Piazzi named the object Ceres**
  - **Initial size estimates varied wildly 260-2600km**
  - **Now known to be about 950km in diameter**
    - **Ceres is small, dark, far from the Sun and far from the Earth**
    - **Can’t see it by eye – but small binoculars are enough**





- **What about the Titus-Bode 'law'**
  - **Ceres appeared to follow the same prediction**
  - **…but, later discovery of Neptune (1846) did not**
  - **Titus-Bode law no longer considered significant**

Planet	Titus-Bode	Observation
Mercury	0.4	0.39
Venus	0.7	0.72
Earth	1.0	1.0
Mars	1.6	1.52
Ceres	**2.8**	**2.8**
Jupiter	5.2	5.2
Saturn	10	9.5
Uranus	19.6	19.2
Neptune	**38.8**	**30.1**



- **The missing planet found? – Yes and No**
- **Other discoveries started to trickle in**
  - **Pallas, Juno, Vesta discovered 1801-1807**
  - **Astraea, Hebe 1845-1847**
- **Started to become obvious that this wasn't just a small planet…**

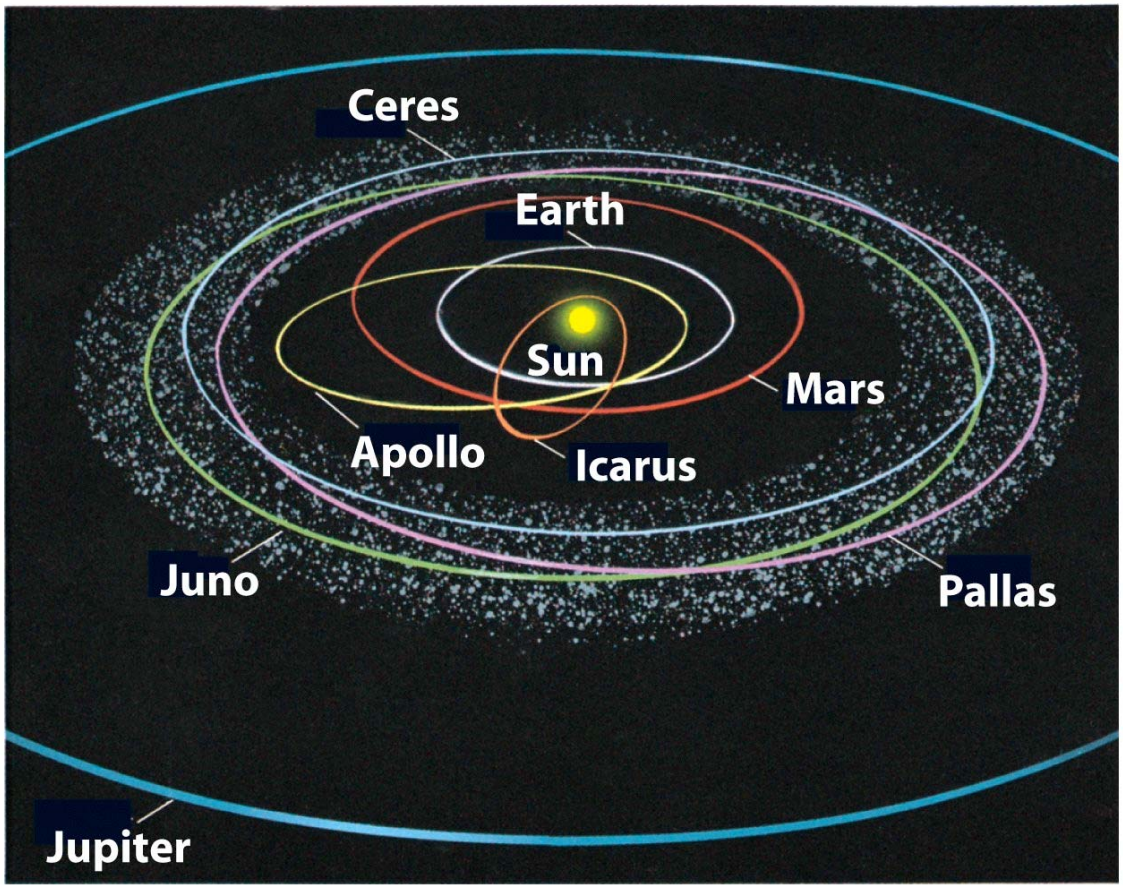


Figure 15-3
Universe, Eighth Edition

- **Astronomical photography – Wolfe 1890s**
  - **Discovered hundreds of objects**
  - **Long-time exposure reveals moving objects**
- **Current population estimate for asteroids >1 km is millions**
  - **Now a source of irritation for astronomers**
  - **Many asteroids seen and not reported**

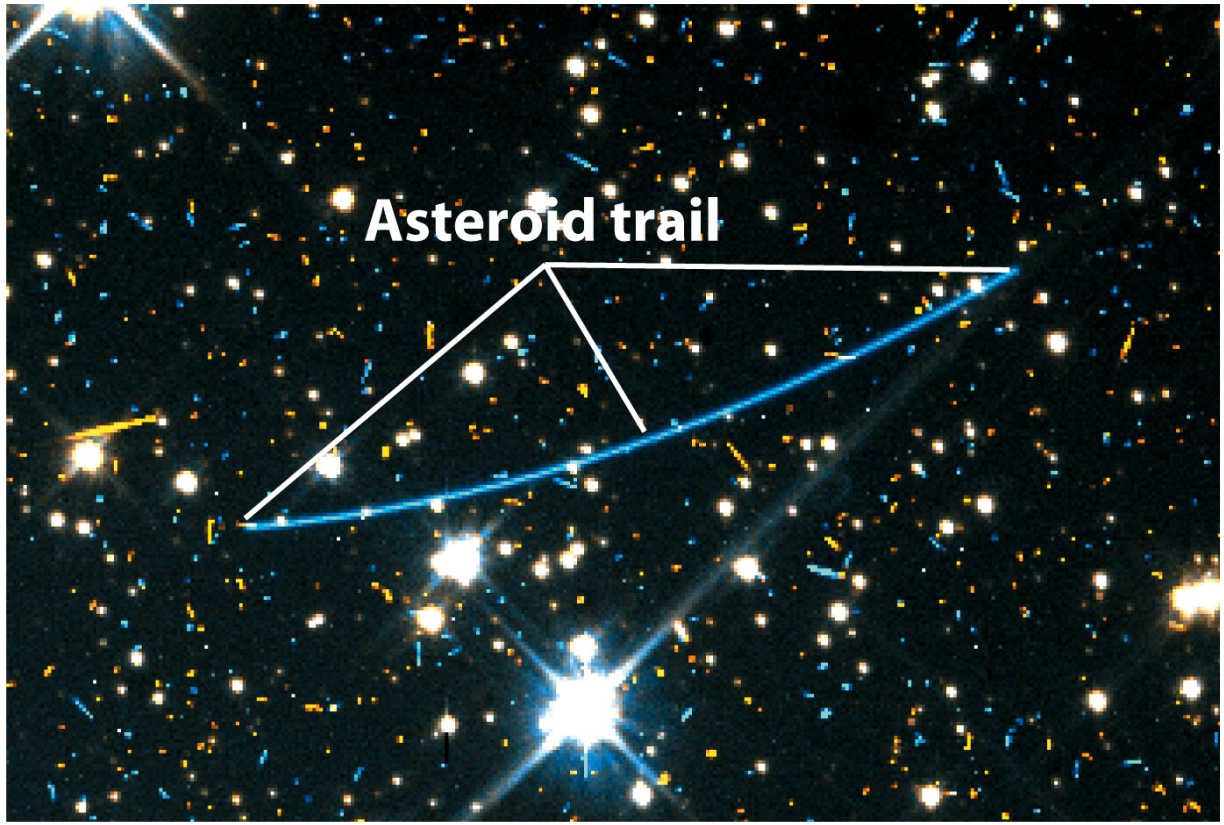
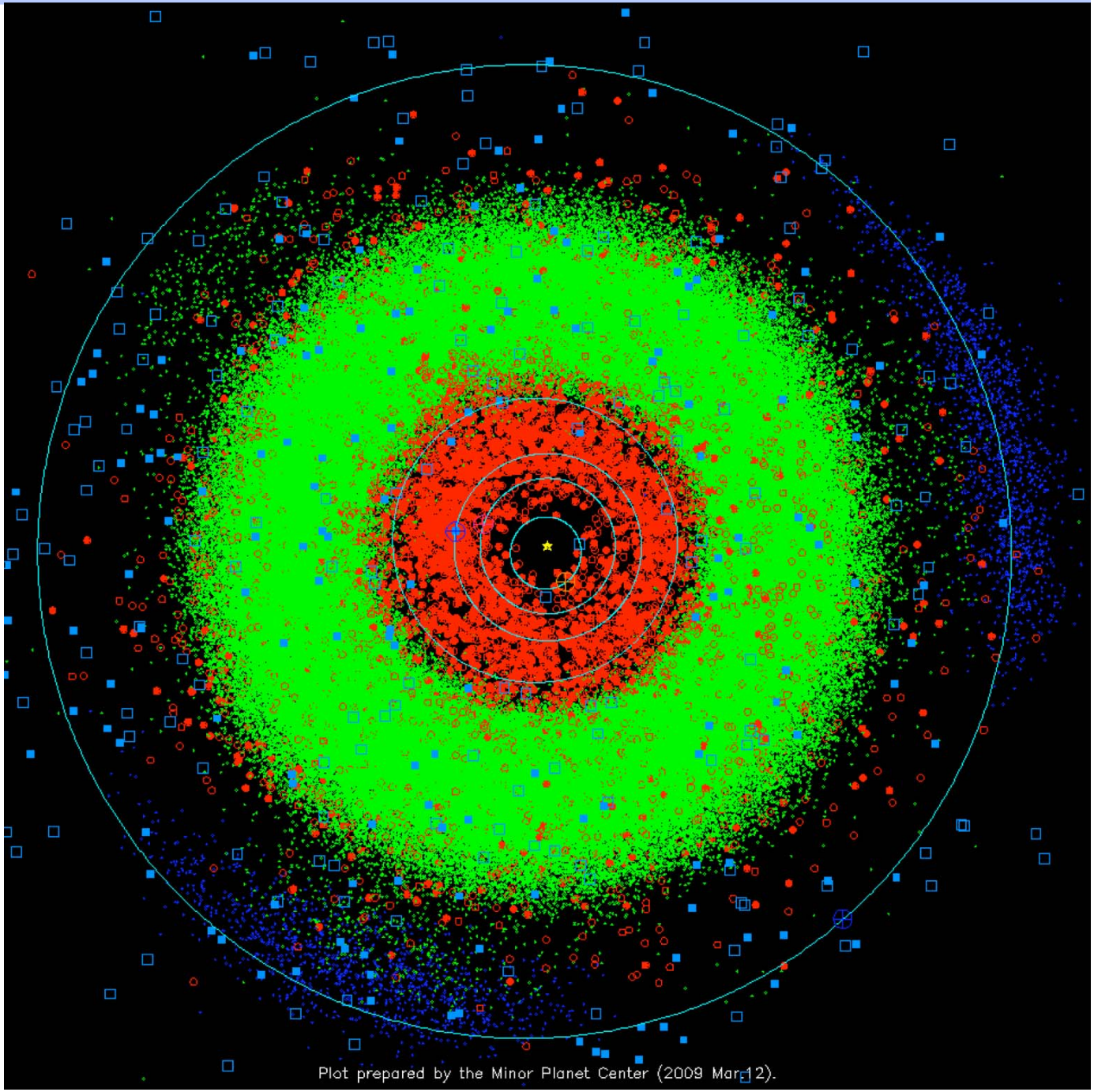
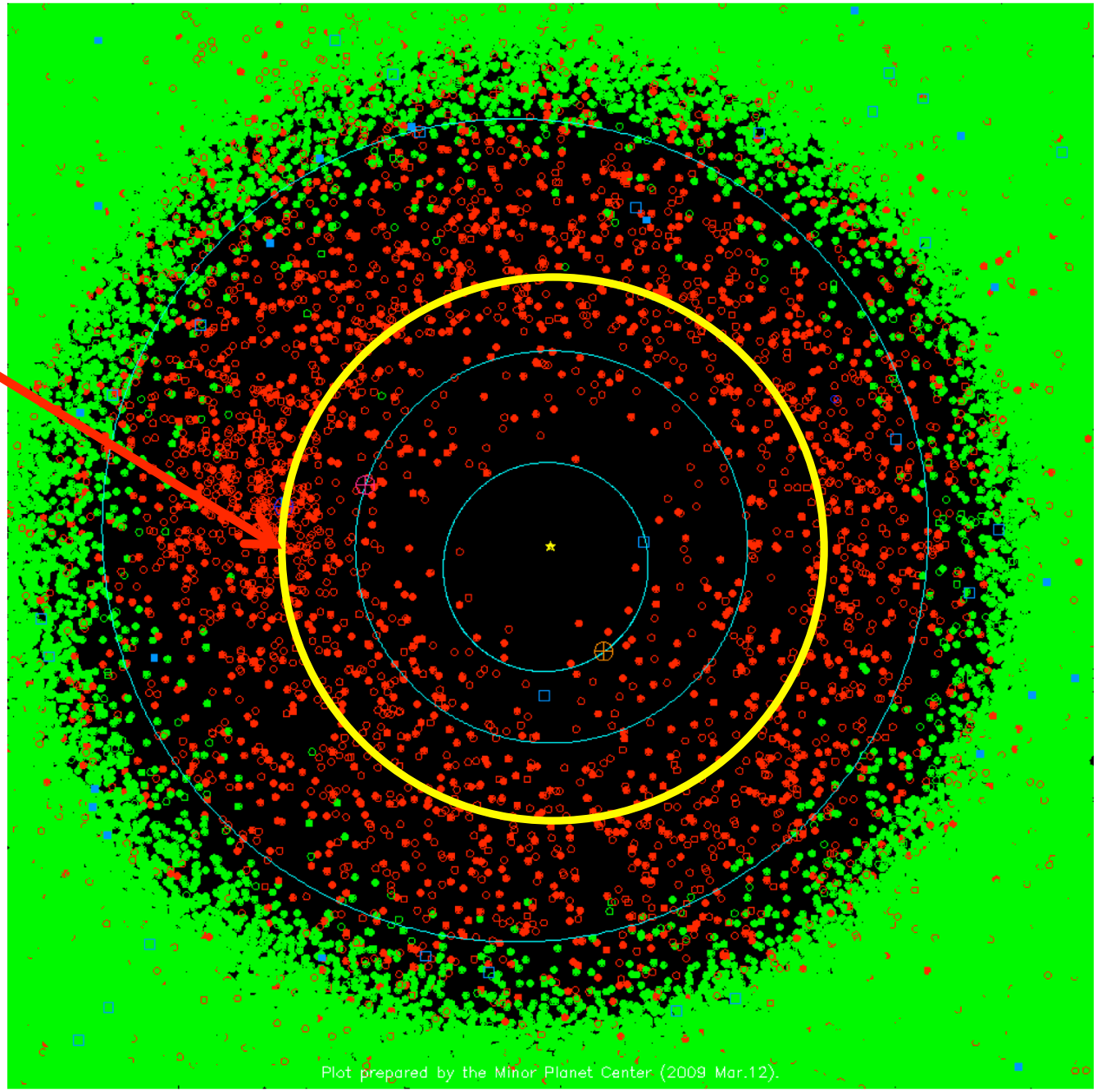


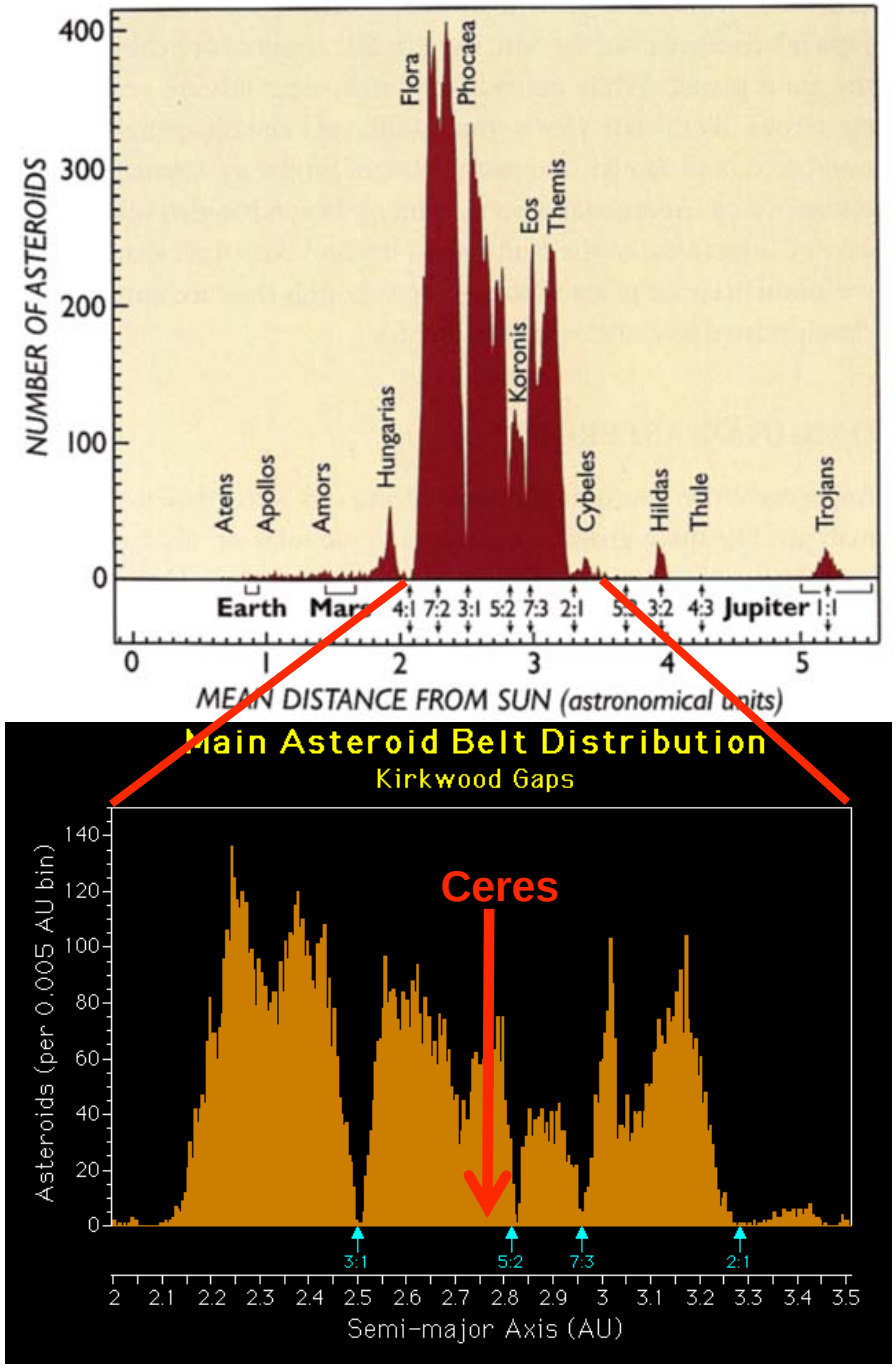
Figure 15-2
Universe, Eighth Edition

- **The solar system this morning.**
  - **Green, red and blue points are asteroids**
  - **Minor planet center keeps track of these**

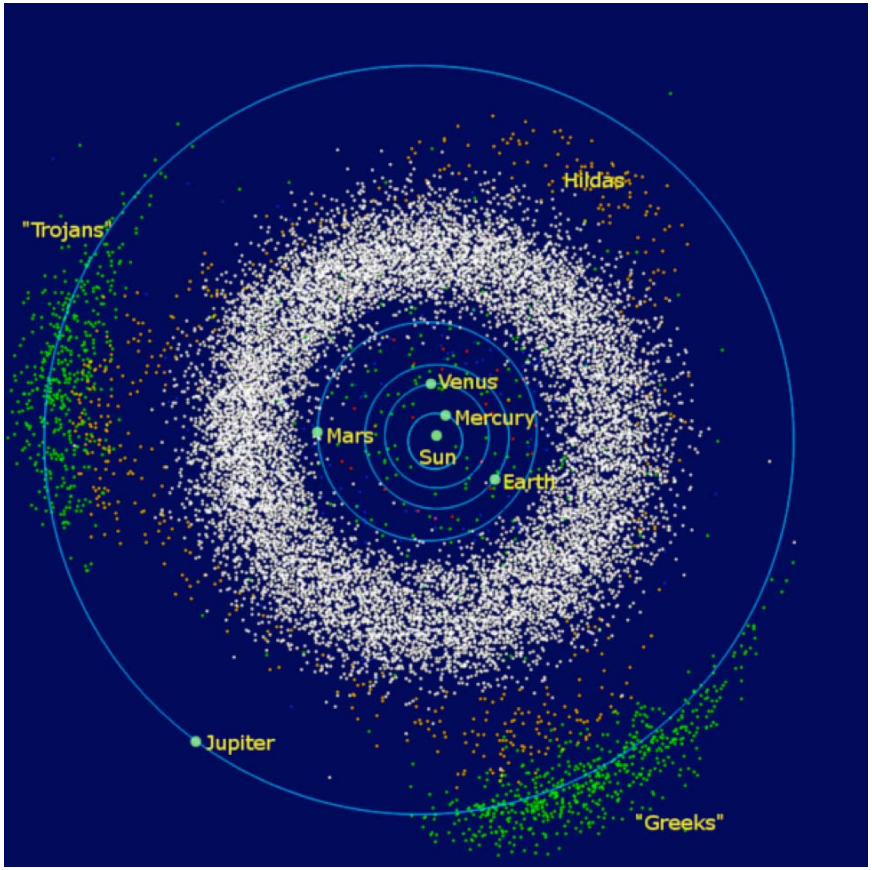


- **Earth's neighborhood is also pretty crowded**

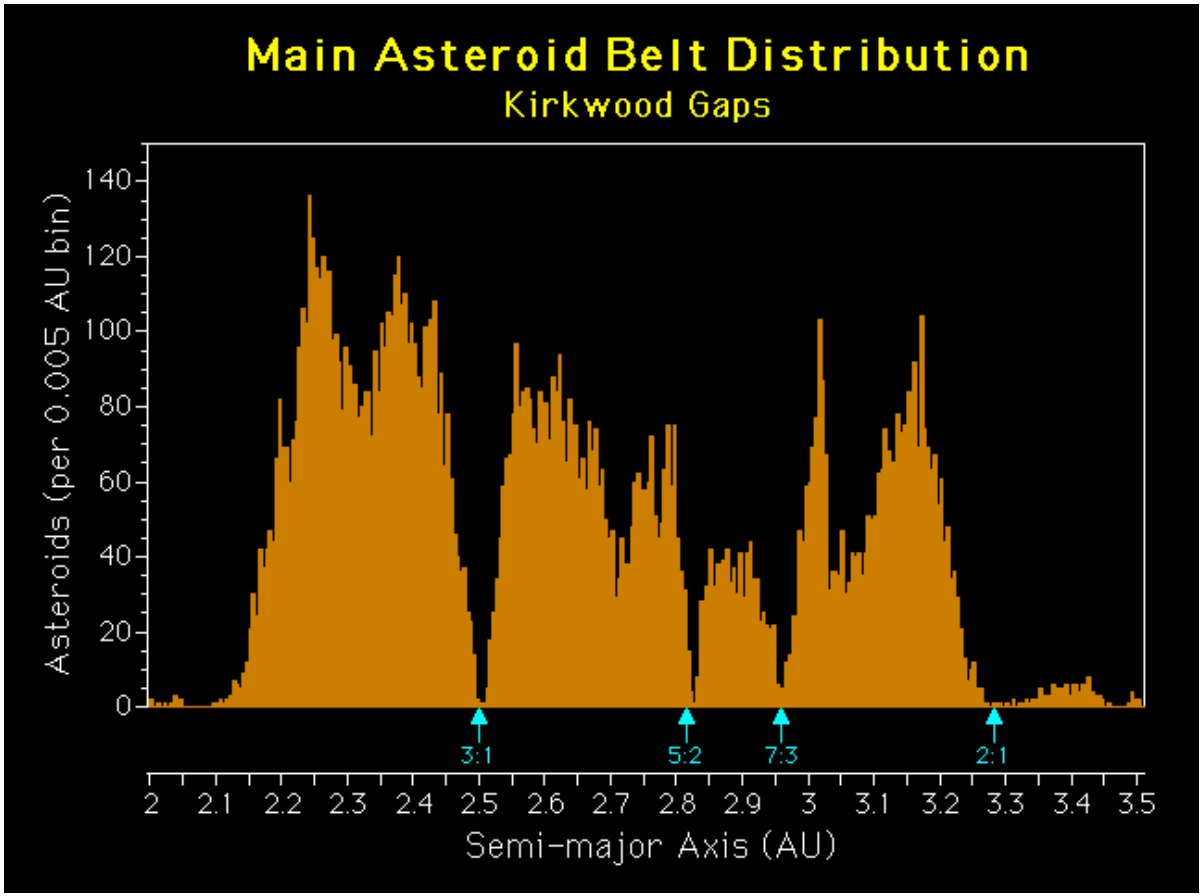




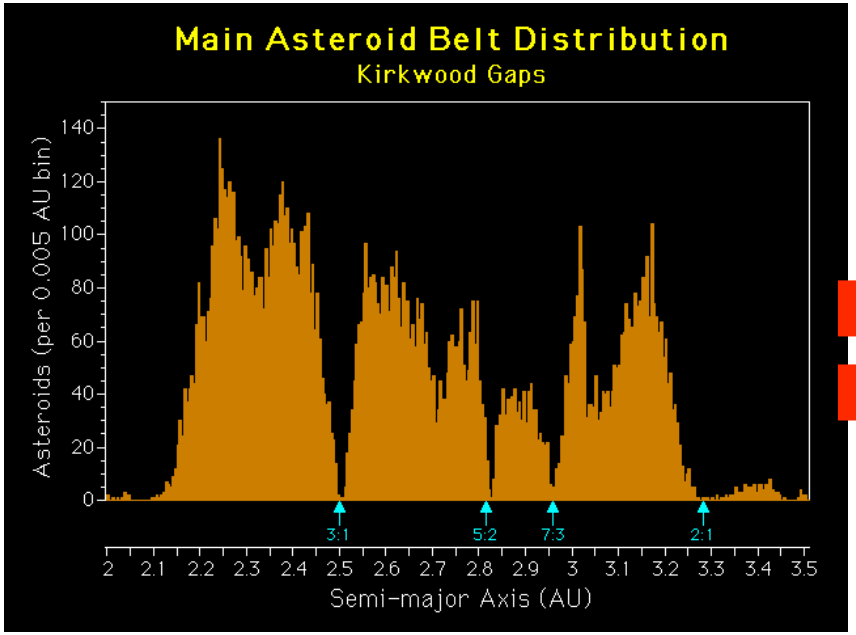
- **Most asteroids lie between Mars and Jupiter in the 'main-belt'**
  - **This belt has gaps though**



- **Asteroids get random perturbations from Jupiter**
  - **Gravitational tugs as they pass by Jupiter's position**
- **Asteroids with certain periods get perturbed at the same point in their orbit again and again**
  - **Orbits of these asteroids become unstable**
  - **This make sure that there are no asteroids left with certain periods**
    - **Or certain semi-major axes**



- **Kirkwood gaps aren't visible**
  - **Asteroids have eccentric orbits so there are asteroids at all locations**
  - **The gaps are only visible when you look at the asteroid periods/semi-major axes**
  - **Not like gaps in the rings of Saturn…**



gaps in the asteroid belt

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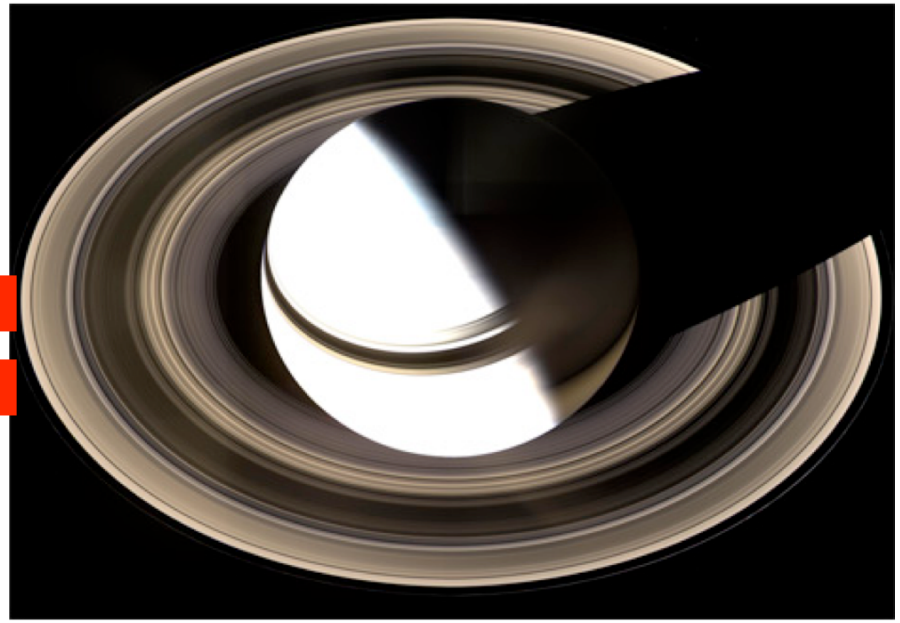
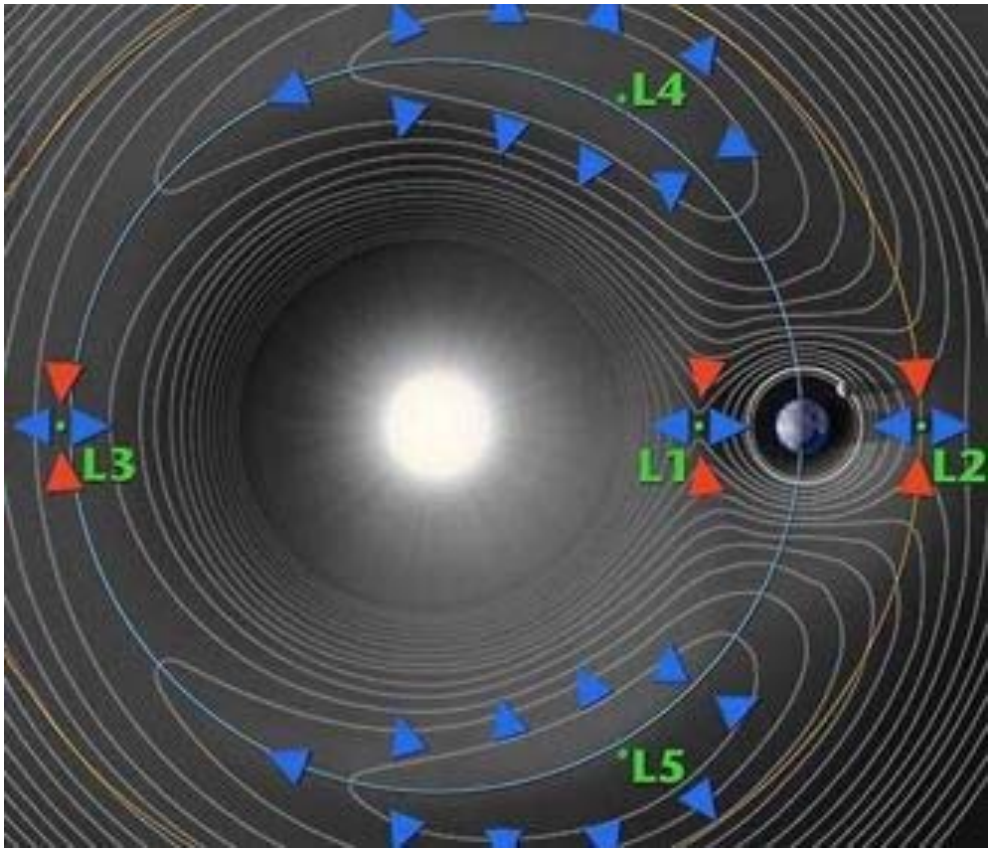
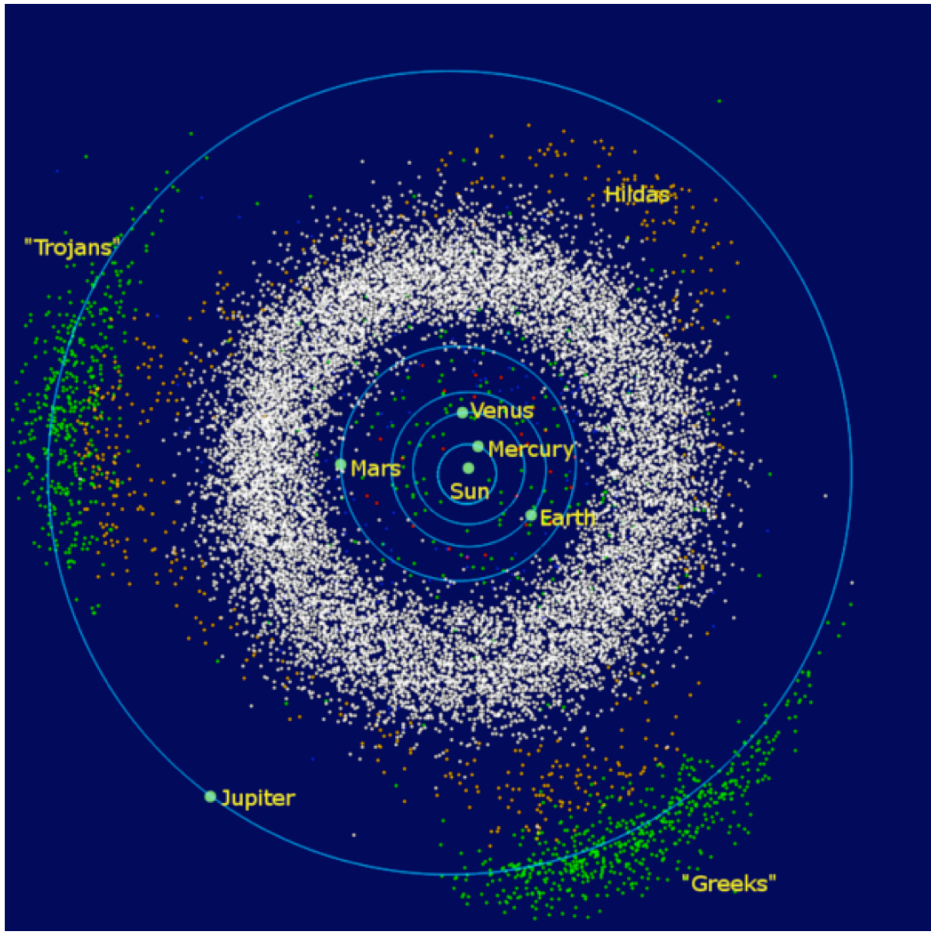


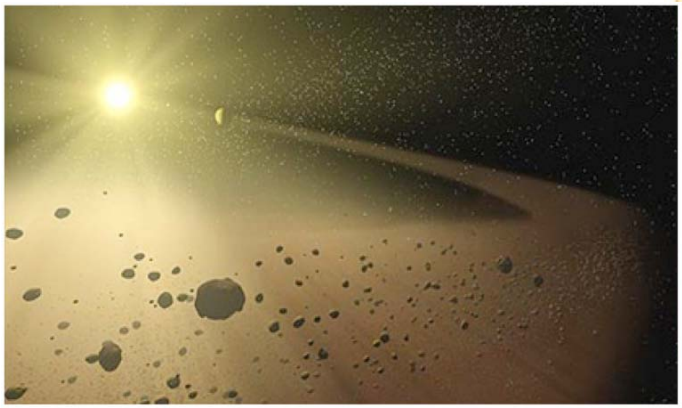
gaps in the rings of Saturn

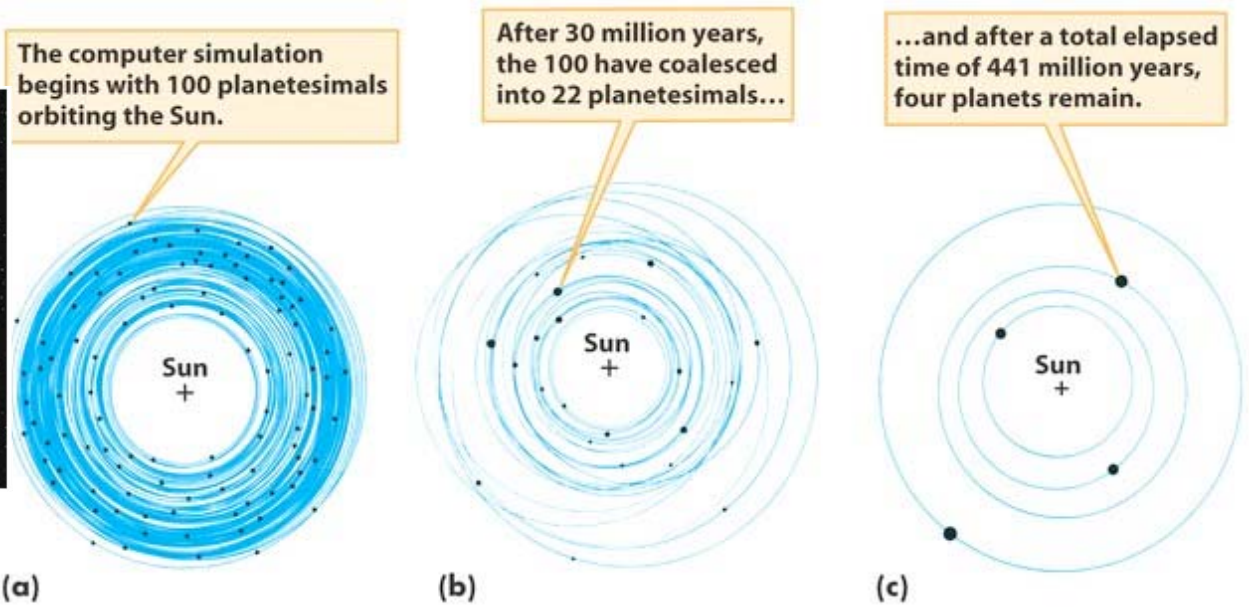
- **Trojan asteroids orbit with Jupiter**
  - **Gravitationally special location – Lagrange points**
  - **Five such points numbered L1 - L5**
  - **Used with the Earth to park satellites**



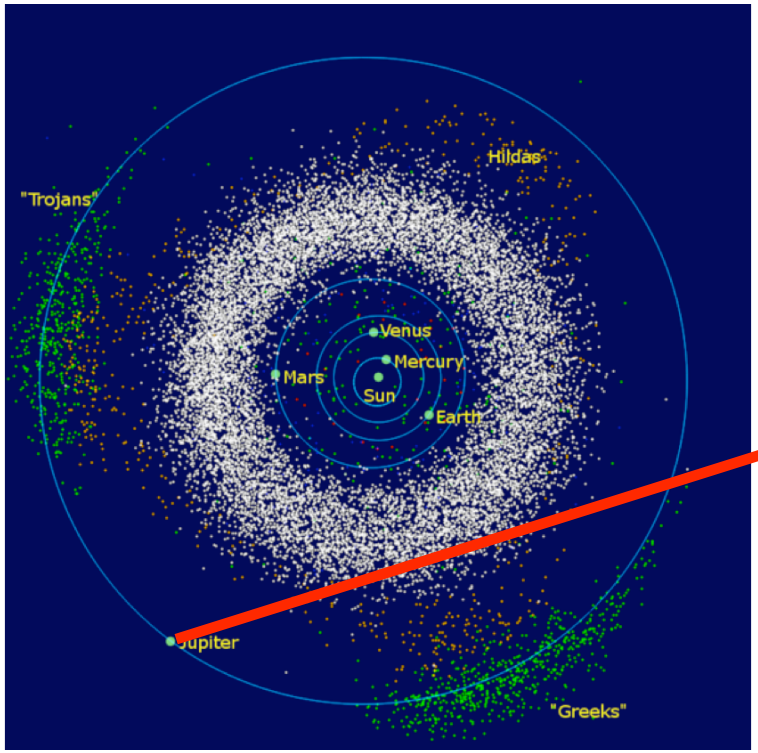


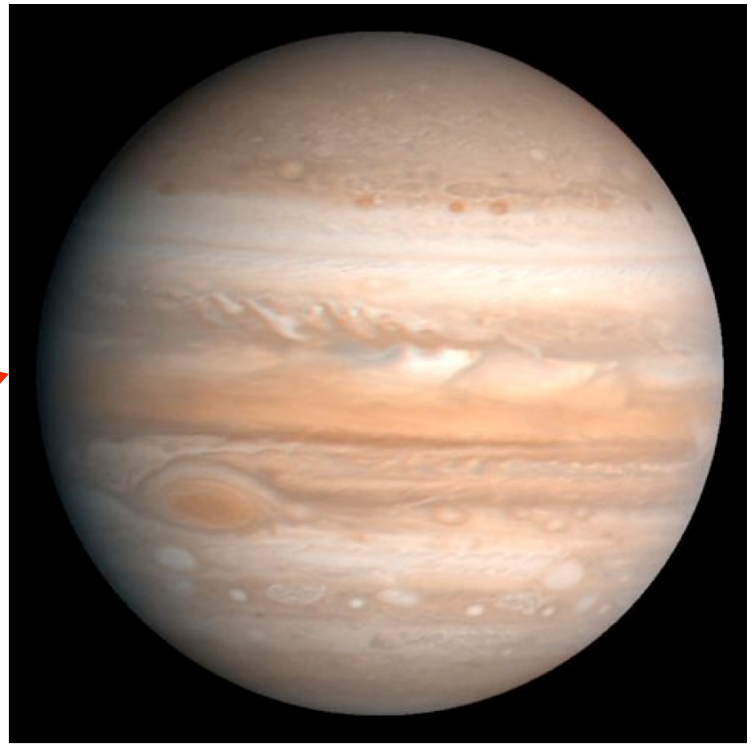
- So where did this belt of tiny rocky objects come from?
- Early theories:
  - The remains of an exploded planet?
  - Components of a planet that never formed?
- What happened elsewhere in the solar system?
  - The sun forms from a dusty disk
  - Rocky planetesimals form from this debris disk
  - Planetesimals eventually join up into large planets via impacts





- **Why didn't the asteroids join up to form a fifth terrestrial planet?**
  - **They're moving too fast relative to each other**
  - **Things that hit each other slowly stick together**
  - **Things that hit each other quickly break each other apart**
  - **Why are the asteroids moving so quickly?**
    - **Jupiter keeps stirring things up**
    - **Without Jupiter's influence we could have had and extra planet there**

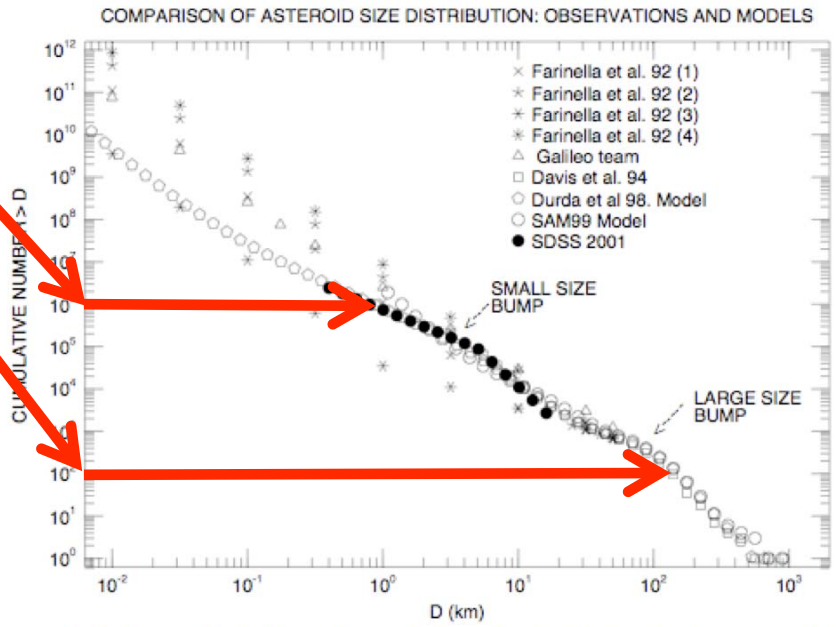




- **What happens when asteroids hit each other?**
  - **The break-up into lots of smaller asteroids…**
  - **The result is an asteroid belt with many small objects and only a few large objects**
  - **Produces families of fragments that stay close together for a while**

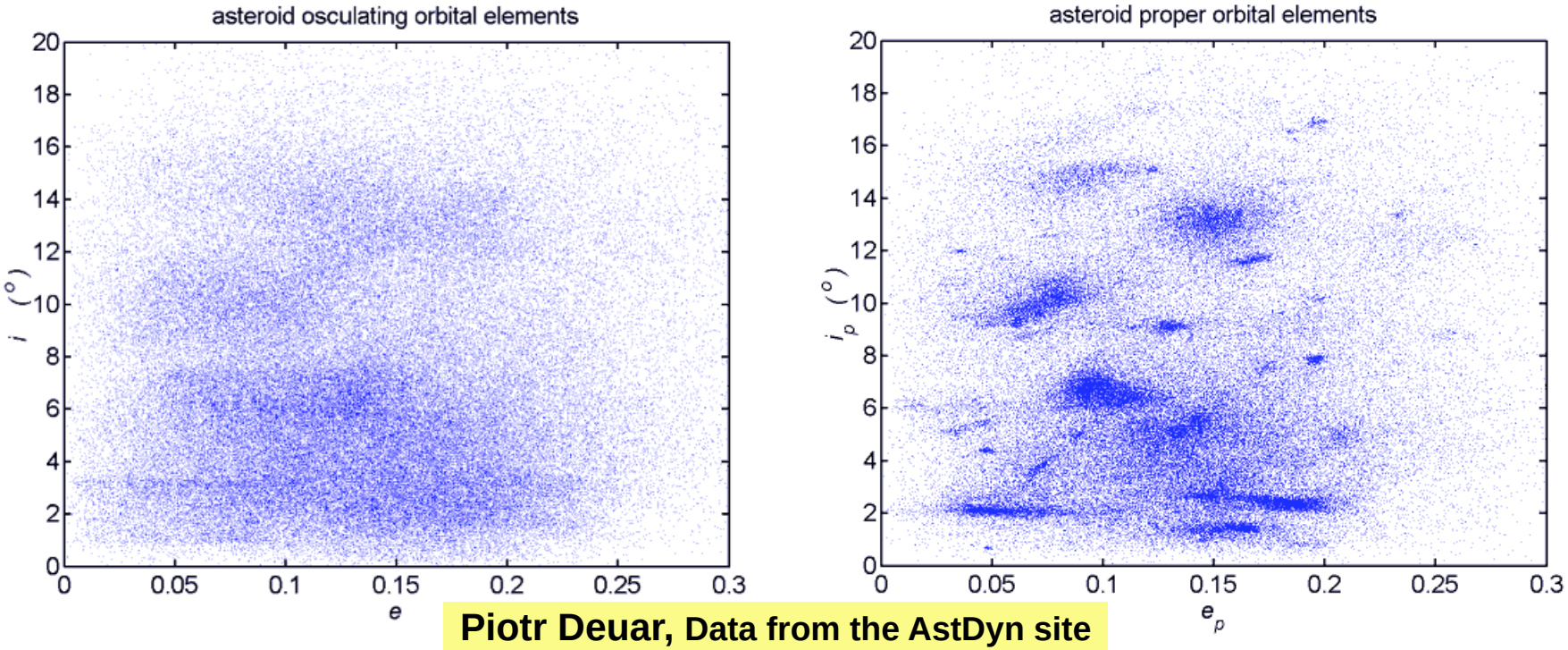
- **~1 million asteroids > 1km**
- **~100 asteroids > 120 km**

- **Asteroids are getting steadily smaller with time (slowly)**



The asteroid size distribution (Davis 2002, in Asteroids III).

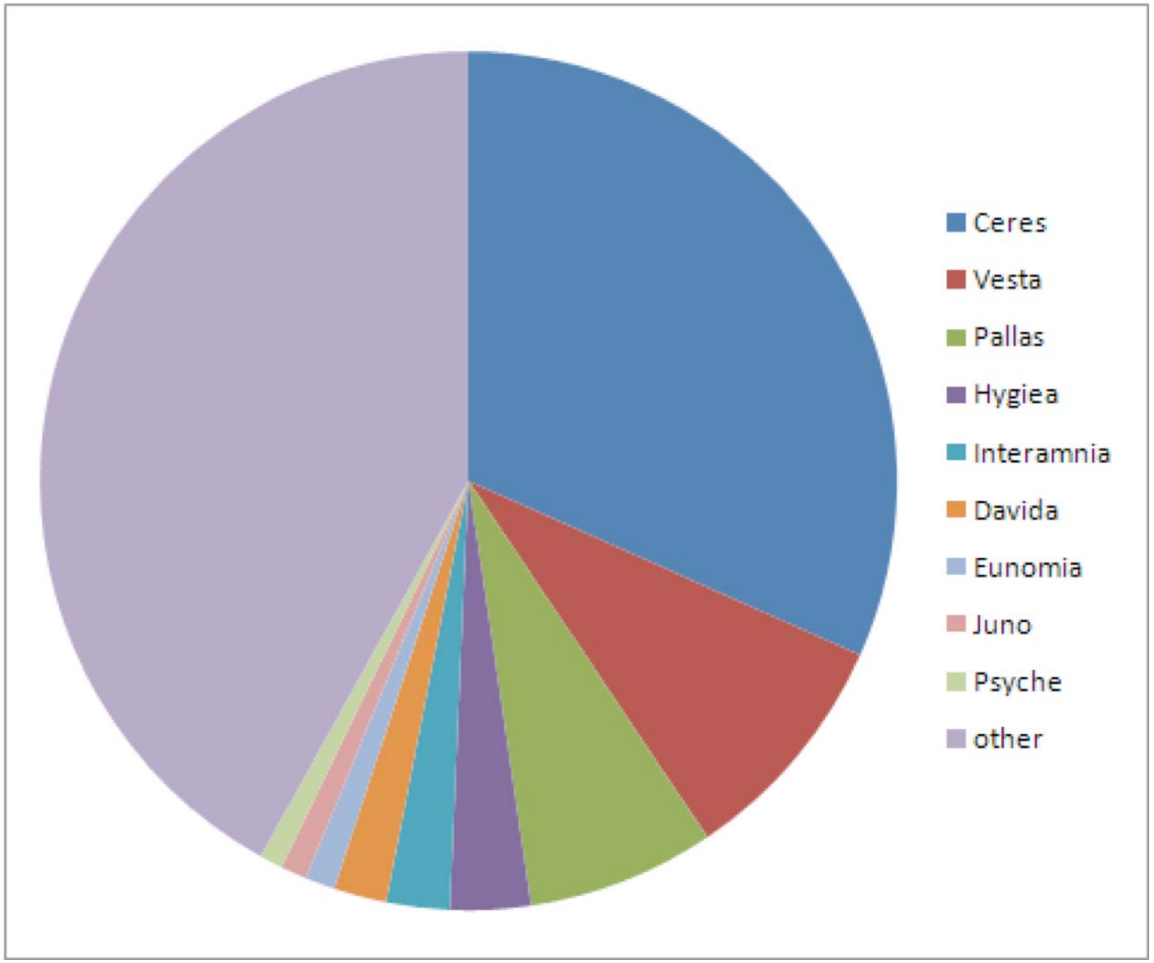
- **Fragments from collisions stick close together and form families of asteroids**
  - **Similar orbital eccentricities and inclinations**
  - **Especially obvious when you check the average eccentricities & inclinations**
  - **Inherited from parent before it broke up**



Piotr Deuar, Data from the AstDyn site

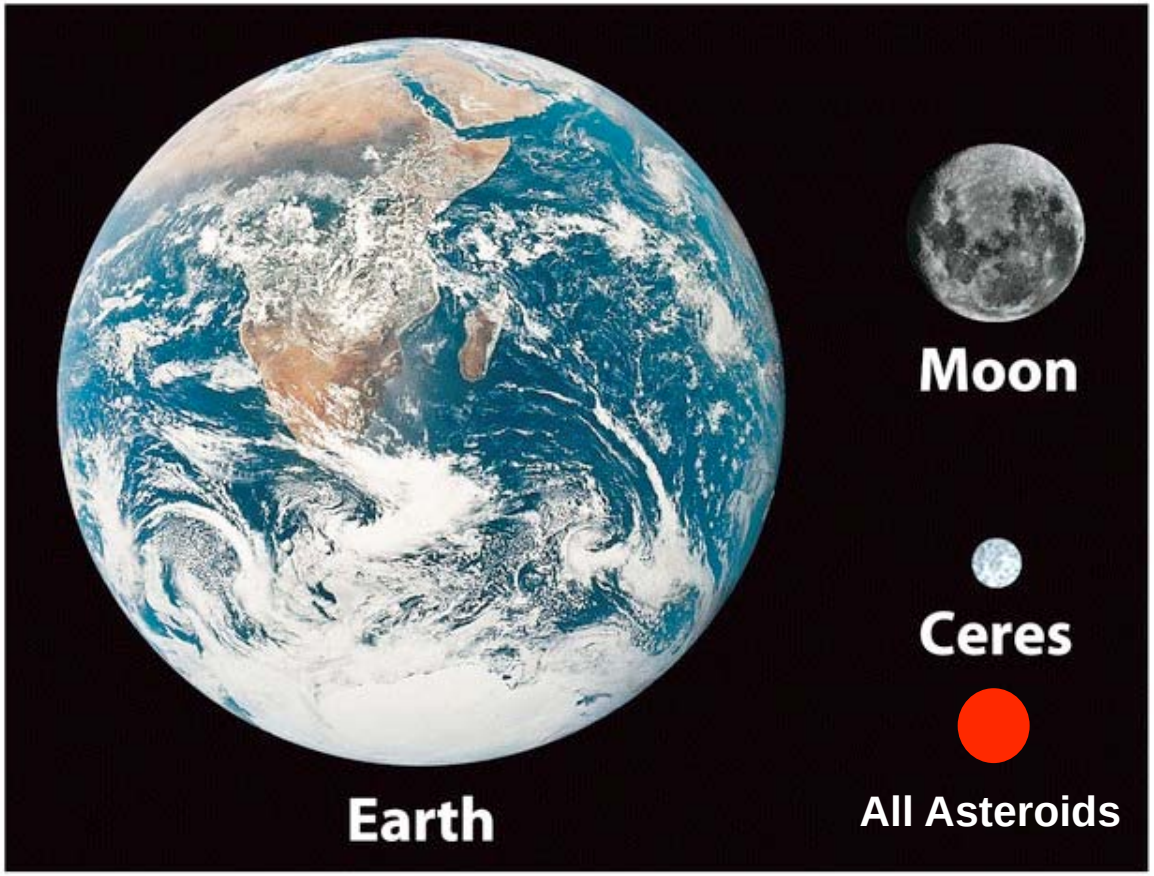
Shapes, sizes, compositions

- **Most of the mass of the asteroid belt is in the four largest asteroids**
  - **How does that compare to the terrestrial planets?**

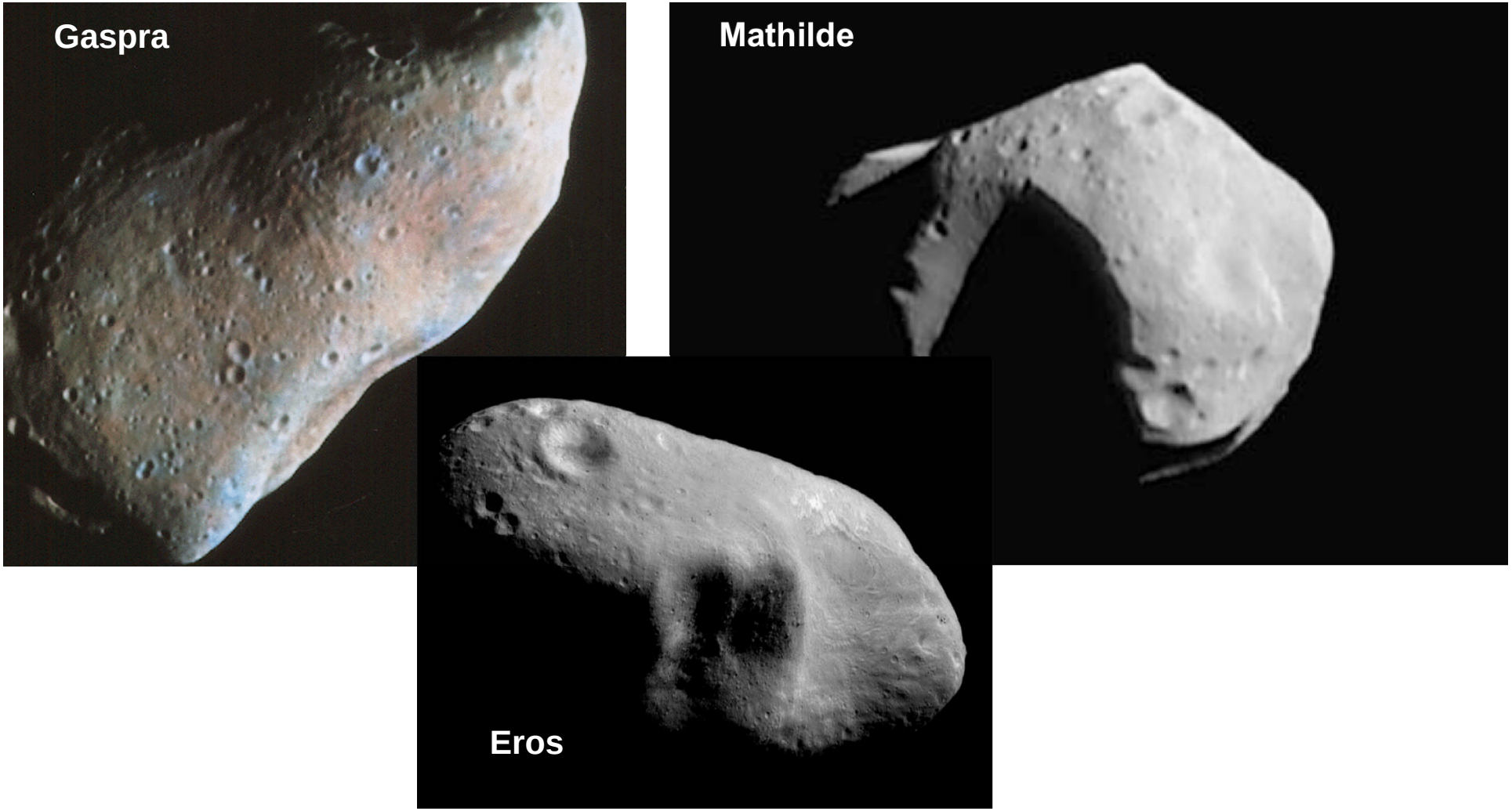


Asteroid Name and Number	Asteroid Class	Diameter (km)
1 Ceres	C	940
4 Vesta	V	576
2 Pallas	B	538
10 Hygeia	C	430
704 Interamnia	D	338
511 Davida	C	324
65 Cybele	C	308
52 Europa	C	292
87 Sylvia	P	282
451 Patientia	C	280
31 Euphrosyne	C	270
15 Eunomia	S	260
324 Bamberga	C	252
3 Juno	S	248
16 Psyche	M	246
48 Doris	C	246
13 Eugenia	C	244
624 Hector	D	232
24 Themis	C	228
95 Arethusa	C	228

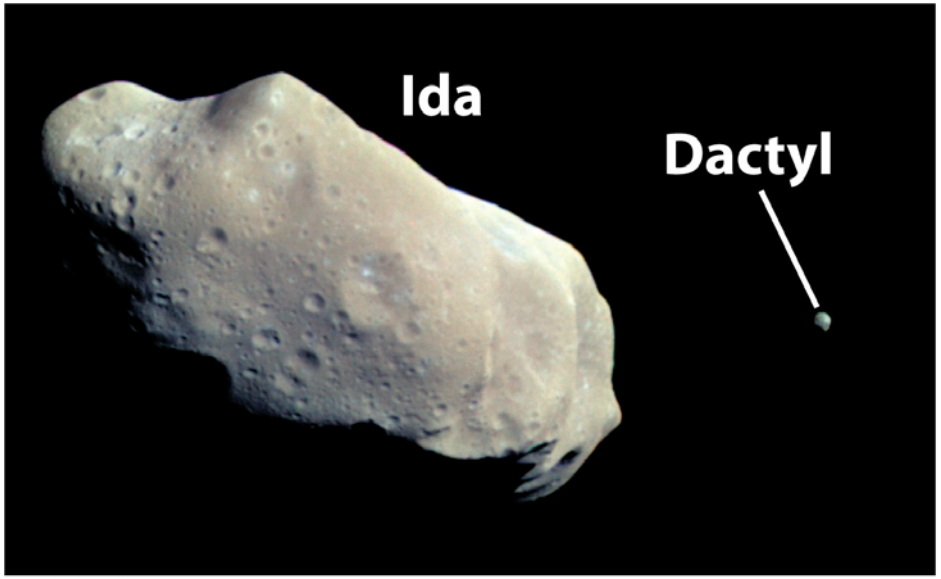
- **Total mass of the asteroid belt is a few percent of the Moon**



- **What shapes do they have?**
  - **Most asteroids are very irregular**
  - **Cratered objects with a regolith – like the Moon**

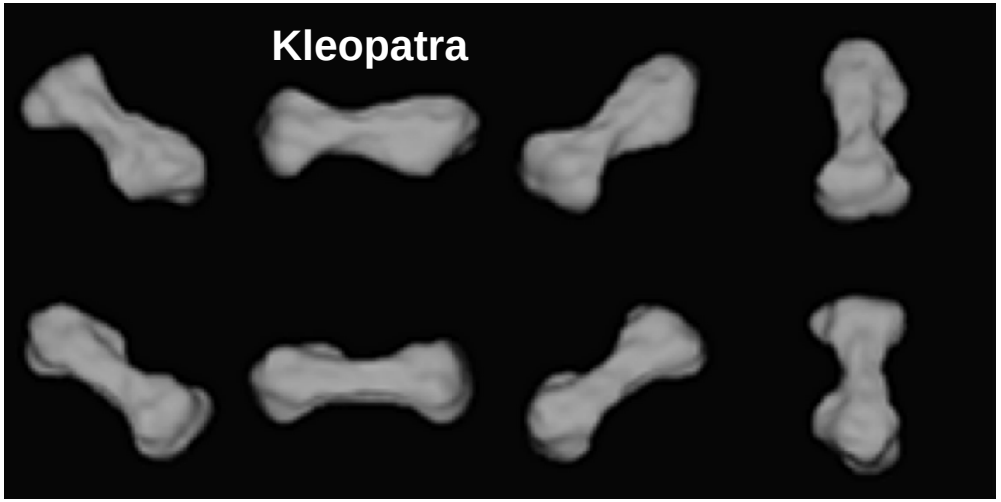


- Some asteroids have moons

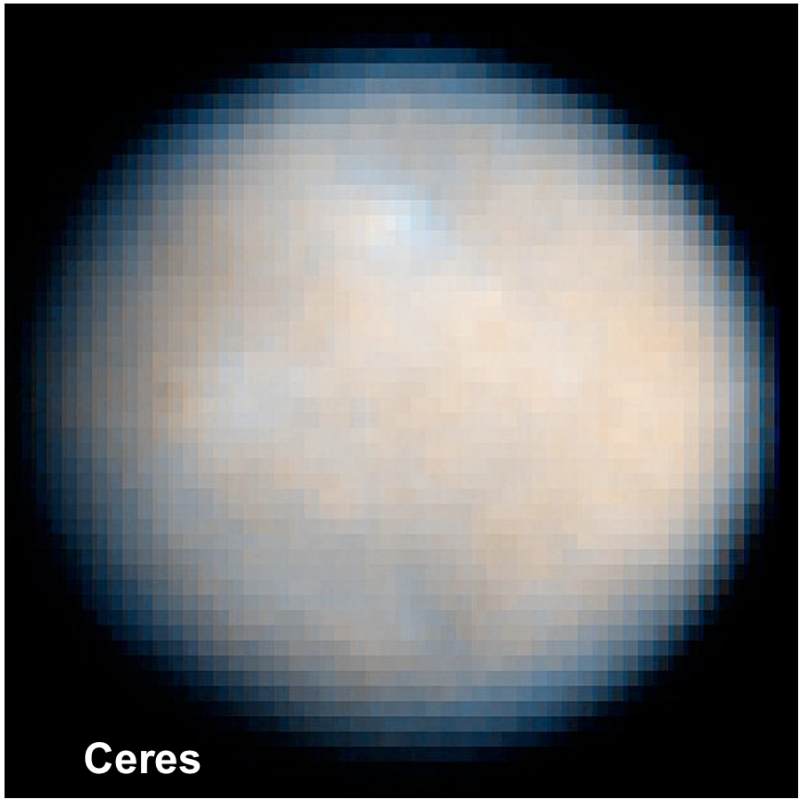


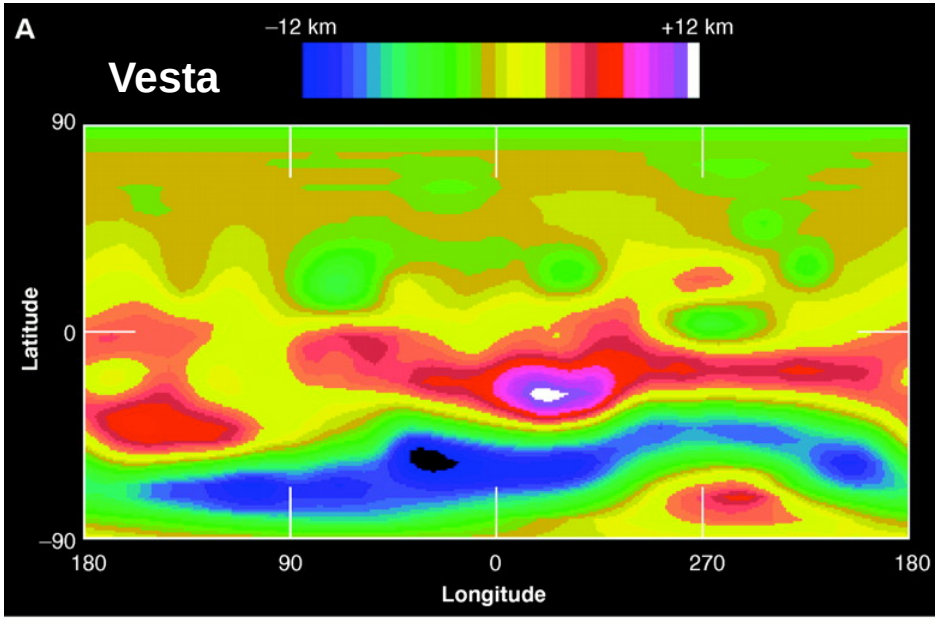
Unnumbered 15 pg 398
Universe, Eighth Edition

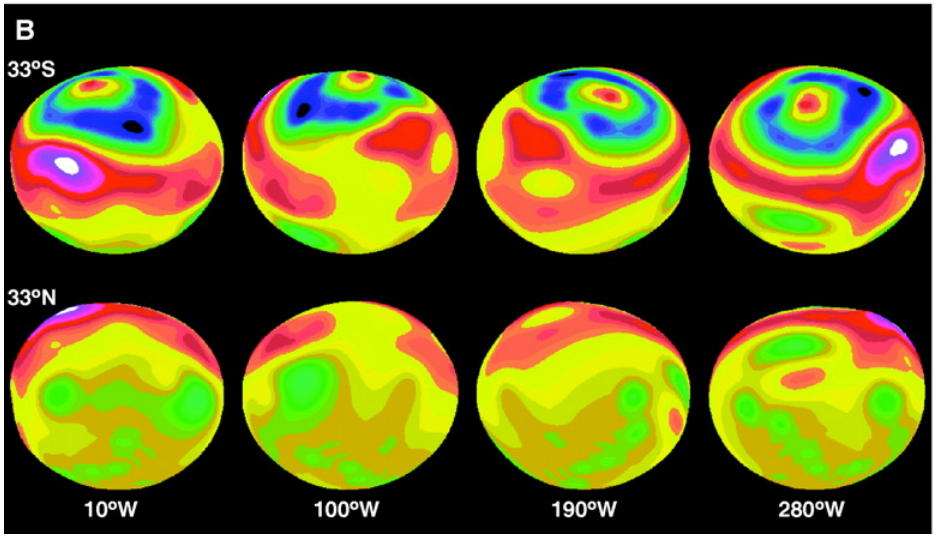
- Some asteroids are just piles of rubble that barely hold themselves together
  - Asteroids that rotate too fast tend to break apart
  - Fast rotators are solid chunks of rock or iron

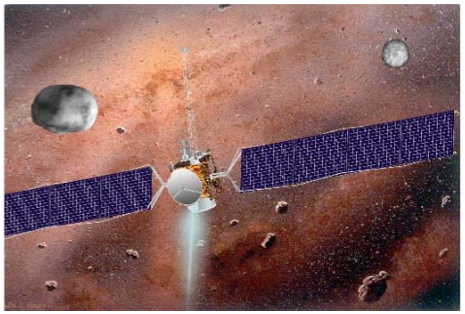


- **Largest asteroids are mostly round**
  - **E.g. Ceres and Vesta**
  - **Vesta may have a large impact basin**



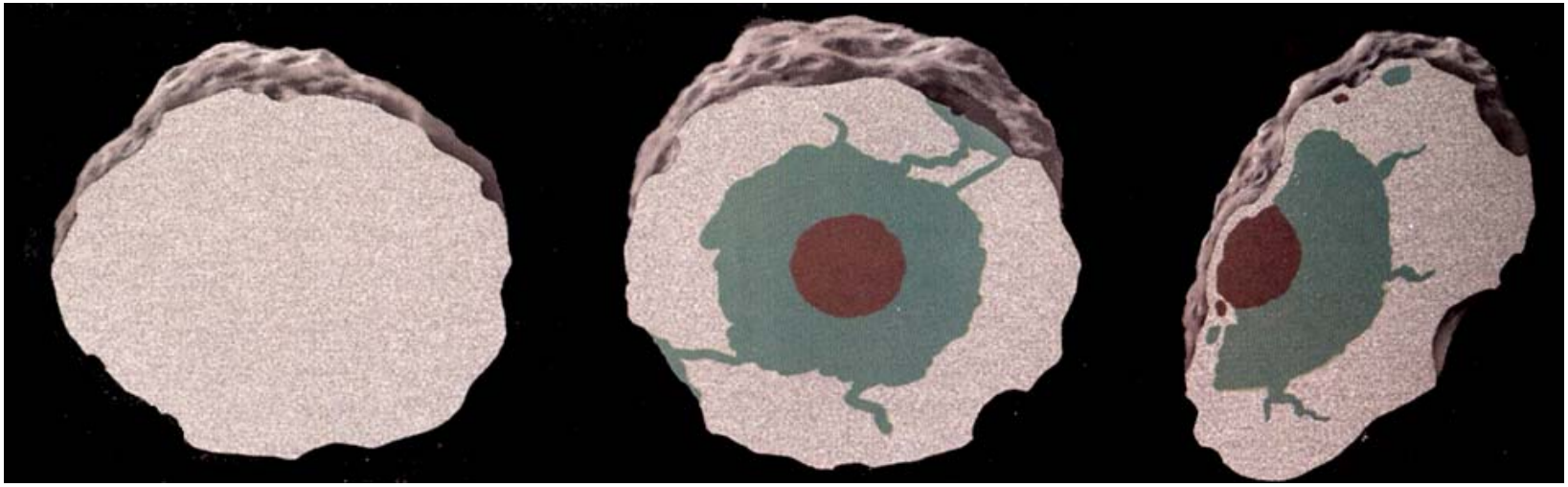






Both to be visited soon by the Dawn mission

- **Asteroids are mostly rocky**
  - **Also some iron (inner belt) and ice (outer belt)**
  - **The larger ones also differentiated**

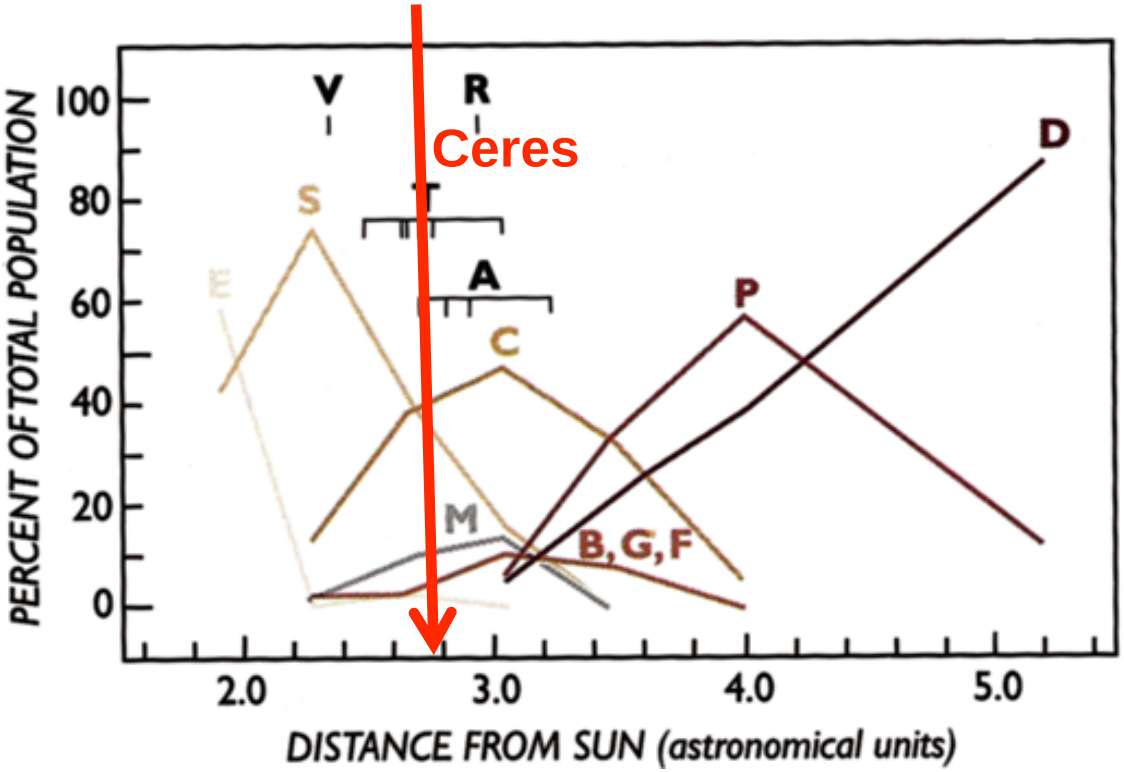


  - **Breakup of differentiated bodies produces fragments that are purely iron or purely rock**
  - **Some asteroids are almost solid iron…**

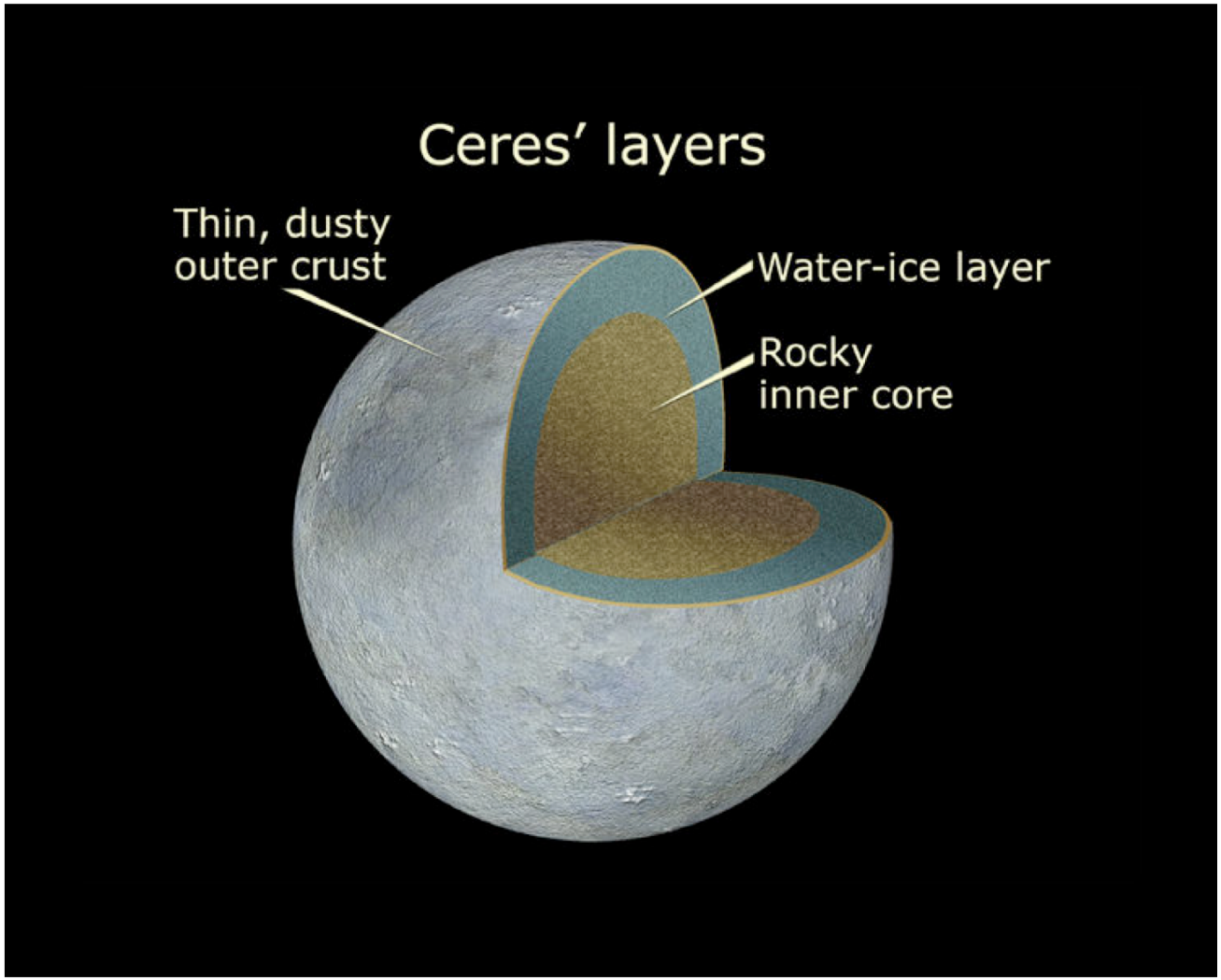
- Asteroids are classified by color and spectra features
- Compositional zoning in the asteroid belt
  - Asteroids with a < 2.7 AU – No sign that rocks were affected by water
    - Dominated by S-type asteroids
    - Differentiation, metallic cores – implies melting of silicates
  - Asteroids with 2.7 AU < a < 3.4 AU – Evidence that rocks were affected by water
    - Dominated by C-type asteroids
    - Clay minerals – implies melting of ice
  - Asteroids with a > 3.4 AU – no hydration (ice never melted)
    - Dominated by D-type asteroids
    - Primitive (unprocessed) objects

The bottom line is more melting happened closer to the Sun early in the solar system

Probably due to short-lived radioactive isotopes



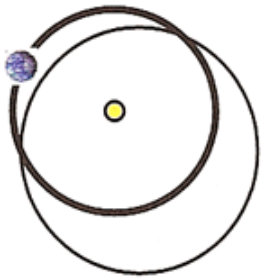
- **Ceres is about 25% water ice**
  - **Probably differentiated into a rocky core and a water ice mantle**
  - **It's possible (but unlikely) that some of this water is still liquid**
  - **A sub-surface ocean on Ceres? – We'll know in a few years…**



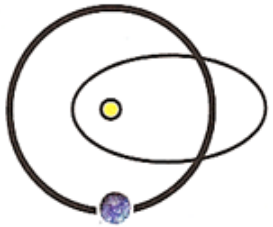
Near-Earth asteroids

- Earth is surrounded by asteroids (NEOs)
  - These objects have short lifetimes – about 10 million years
  - Most are ejected from the solar system
  - or they crash into the sun or a terrestrial planet – like us…
  - They're being constantly resupplied
- Atens and Apollo cross Earth's orbit – dangerous
- Amors and Apoheles stay outside/inside Earth's orbit – less dangerous

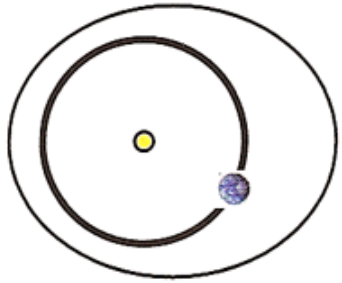
Apollo
Semimajor Axis ≤ 1.0 AU
Perihelion ≤ 1.02 AU
Earth Crossing



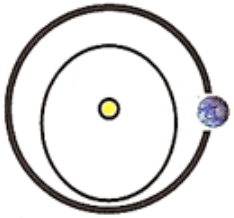
Aten
Semimajor Axis < 1.0 AU
Perihelion ≤ 1.0167 AU
Earth Crossing



Amor
1.02 AU < Perihelion ≤ 1.3 AU

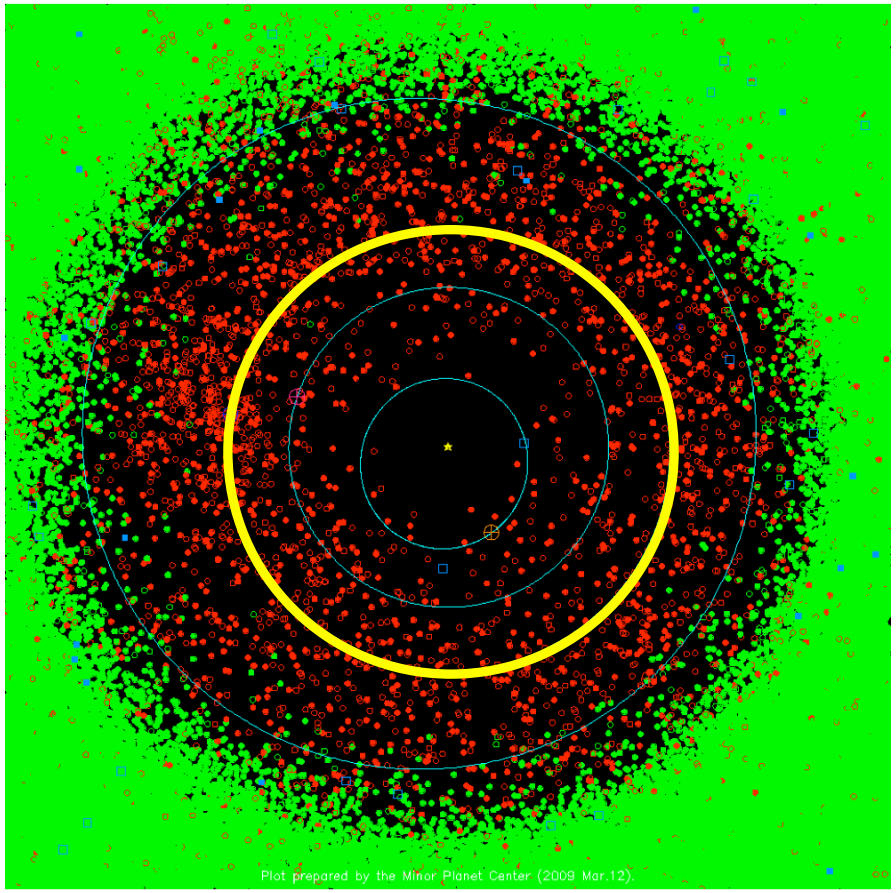


Inner Earth Objects (IEOs)
Apohelion < 0.983 AU
Always inside Earth's orbit
(aka Apohele)

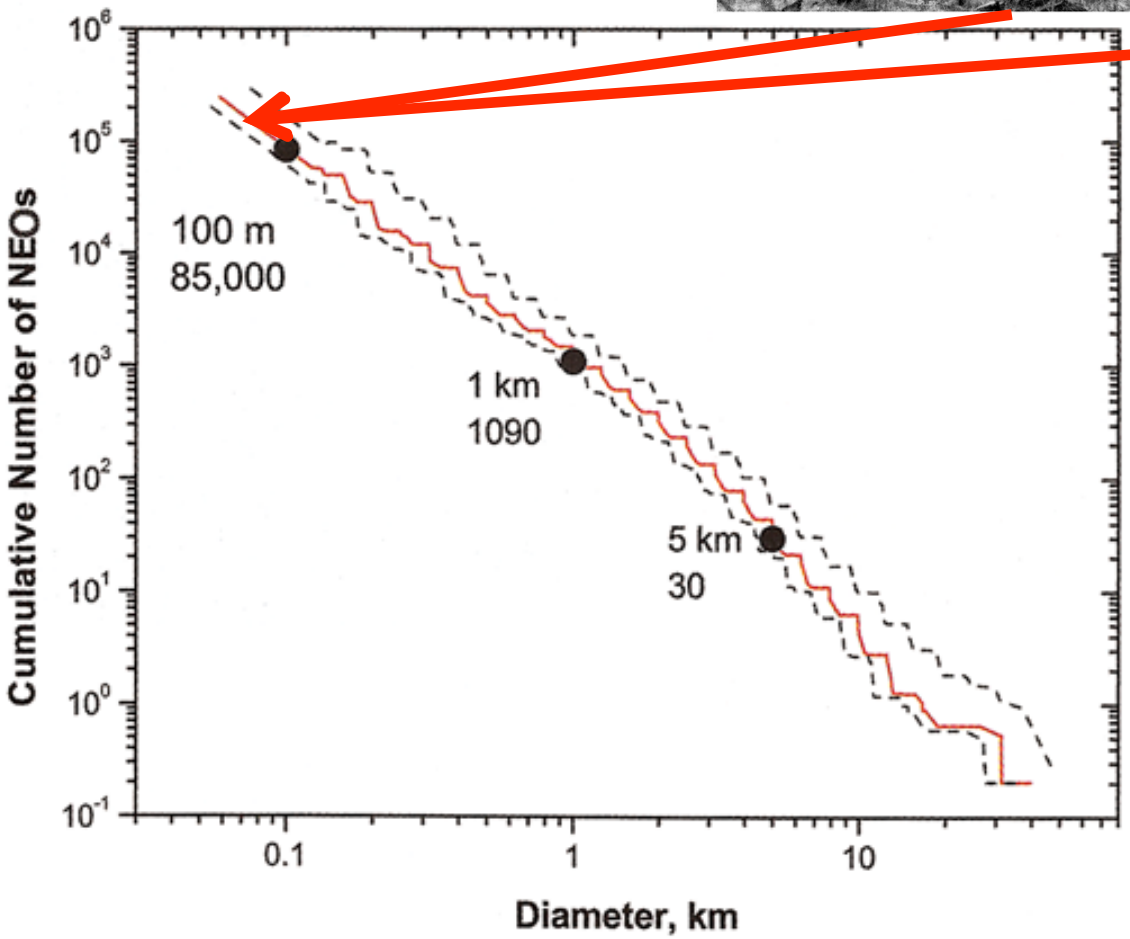


Type	Population
Apollo	62% of known
Aten	6% of known
Amor	32% of known
Aphohel e	Unknown number

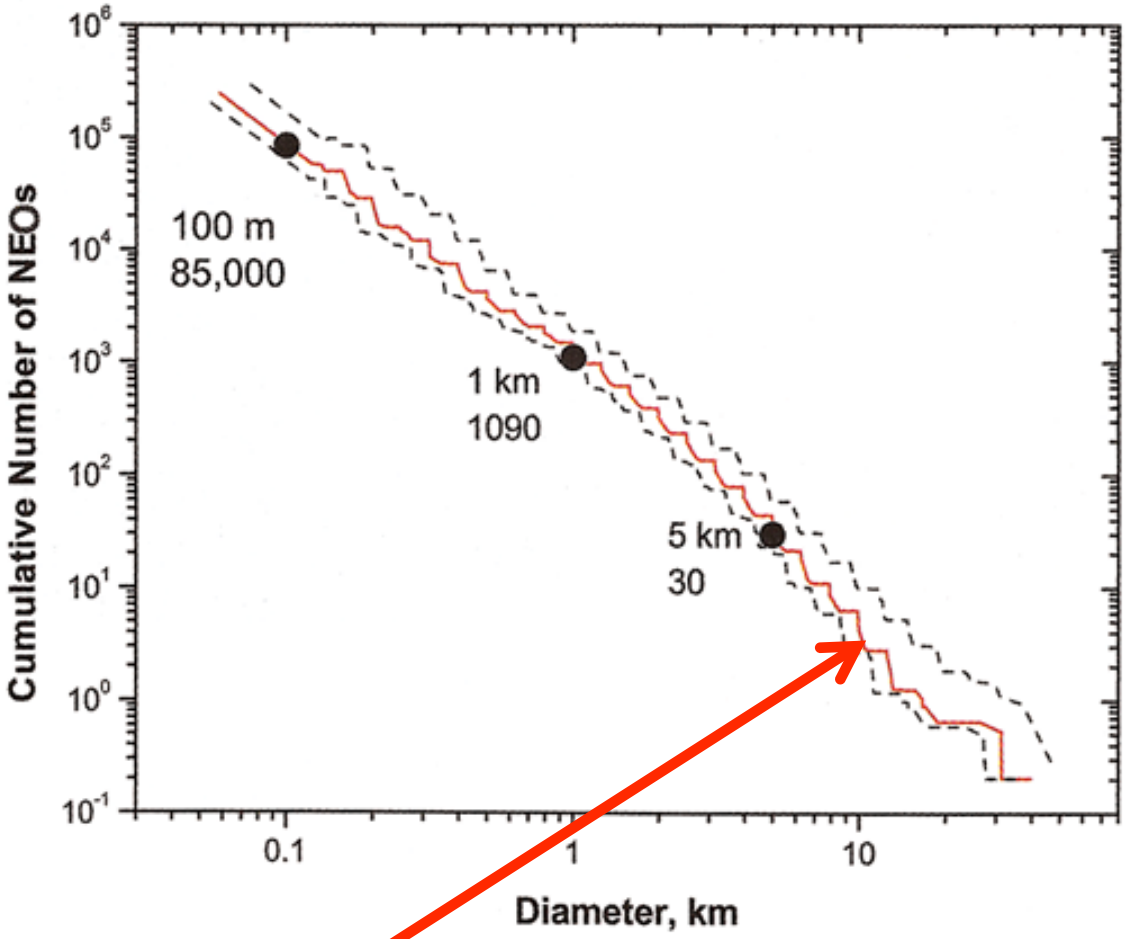
- **Where are these things coming from?**
  - **Collisions in the main belt produce fragments that stray into the Kirkwood gaps**
  - **These fragments get eventually ejected from the asteroid belt by Jupiter**
  - **Some of them end up in the inner solar system**



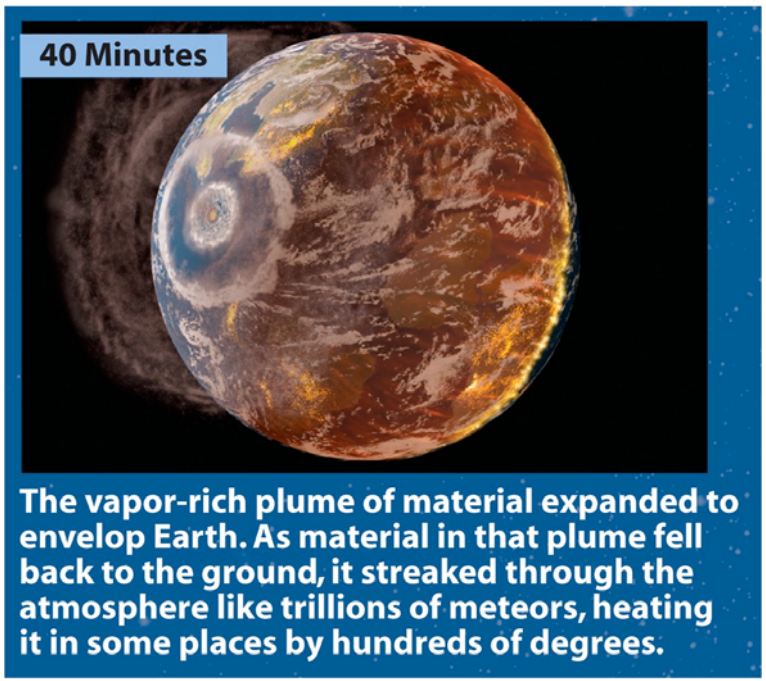
- What's out there?



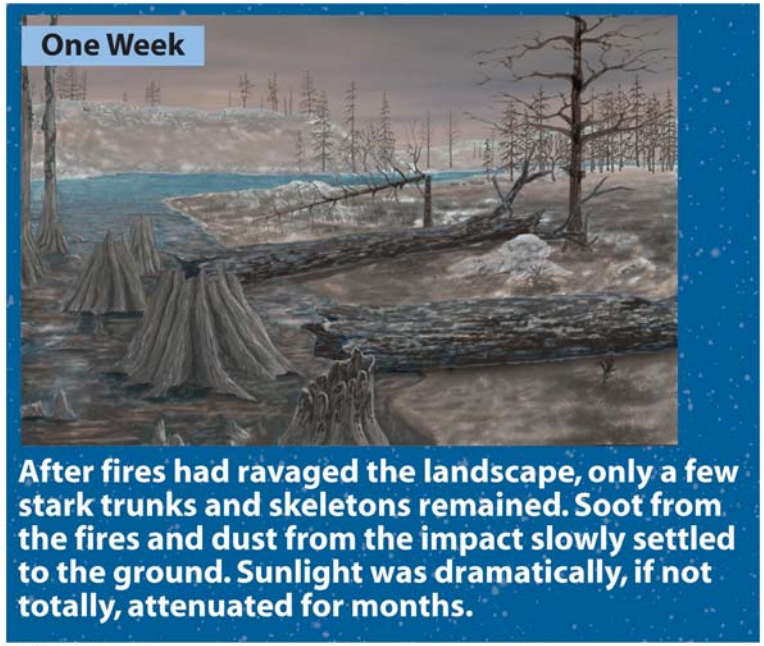
- Tunguska
  - 100 yr event
  - Stony asteroid
- Meteor crater
  - 50,000 yr event
  - Iron asteroid (rarer)



- **Chicxulub event**
  - **Death of dinosaurs**
  - **Global wildfires**
  - **Reentering debris cooked the dinosaurs**



The vapor-rich plume of material expanded to envelop Earth. As material in that plume fell back to the ground, it streaked through the atmosphere like trillions of meteors, heating it in some places by hundreds of degrees.



After fires had ravaged the landscape, only a few stark trunks and skeletons remained. Soot from the fires and dust from the impact slowly settled to the ground. Sunlight was dramatically, if not totally, attenuated for months.

Cosmic Connections 15 pt 4
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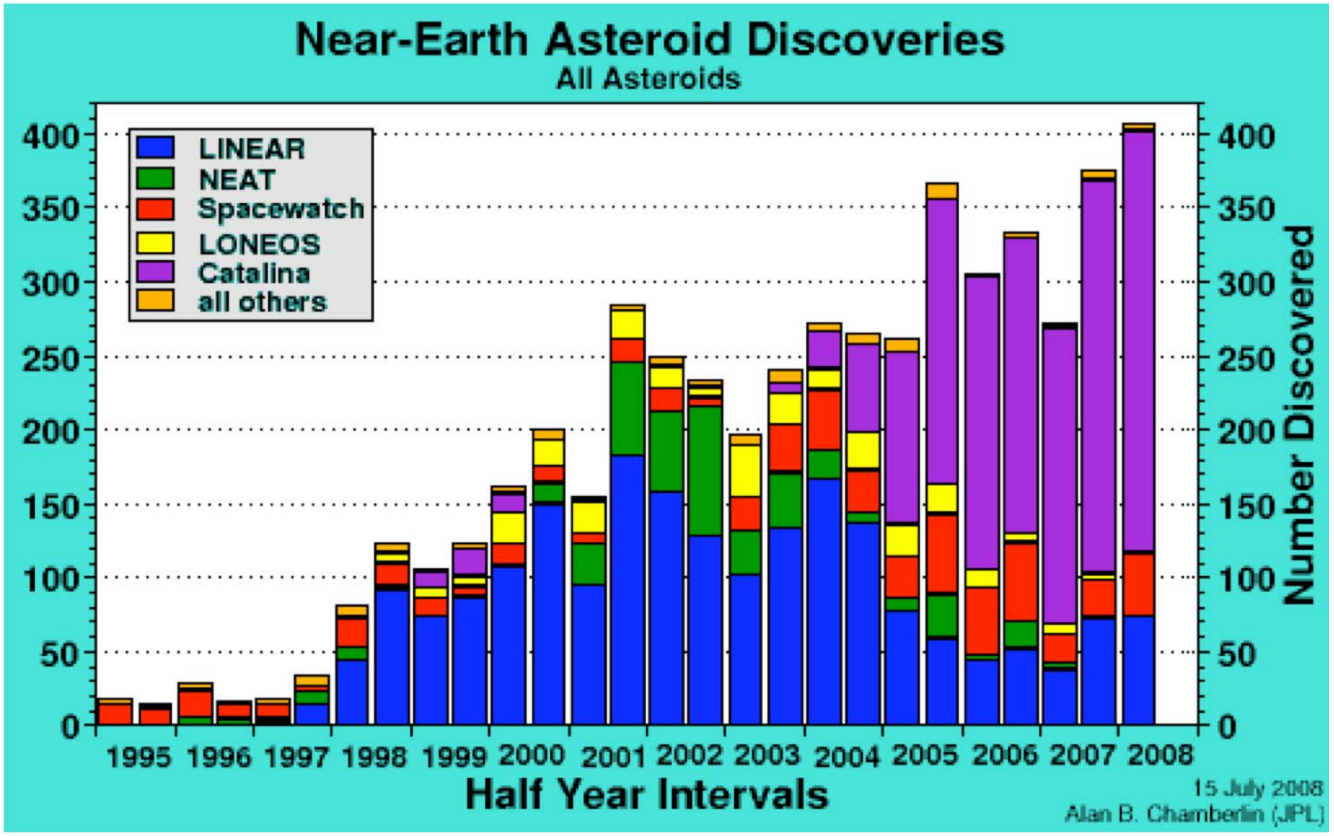
- **What are we doing about it?**
  - **We have programs in place to discover these objects**
  - **..but not many options if we do discover a future collision**
  - **Just predicted an impact over Sudan a few months ago – harmless atmospheric explosion**



Meteorites

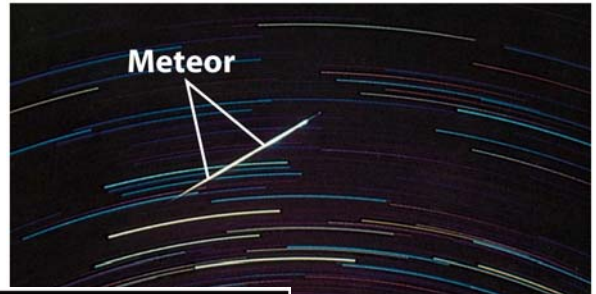


Figure 15-15a
Universe, Eighth Edition
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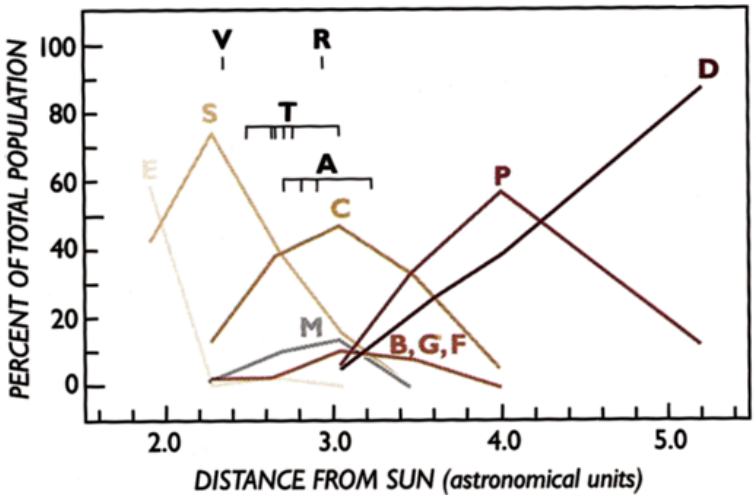
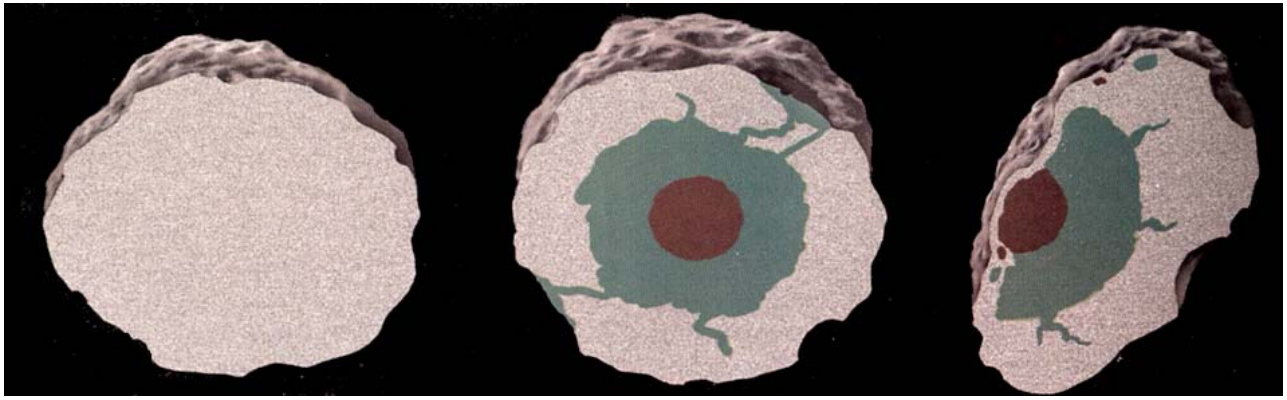
- **Some terminology**
  - **Meteor**
    - Body passing through our atmosphere
  - **Meteorite**
    - Fragments of asteroids on Earth
  - **Meteoroid**
    - Fragments of asteroids in space

- **Meteorites are samples of the asteroid belt**
  - **Inner belt – dry rock and iron**
  - **Middle of the belt – rock altered by water**
  - **Outer belt – primitive solar system material not altered by water**





- **Samples of differentiated bodies**
  - **Crustal samples: Stony meteorites**
  - **Mantle samples: Stony to stony-iron meteorites**
    - **E.g. Pallasite (core mantle boundary)**
  - **Core samples: Iron meteorites**

Willamete meteorite - iron

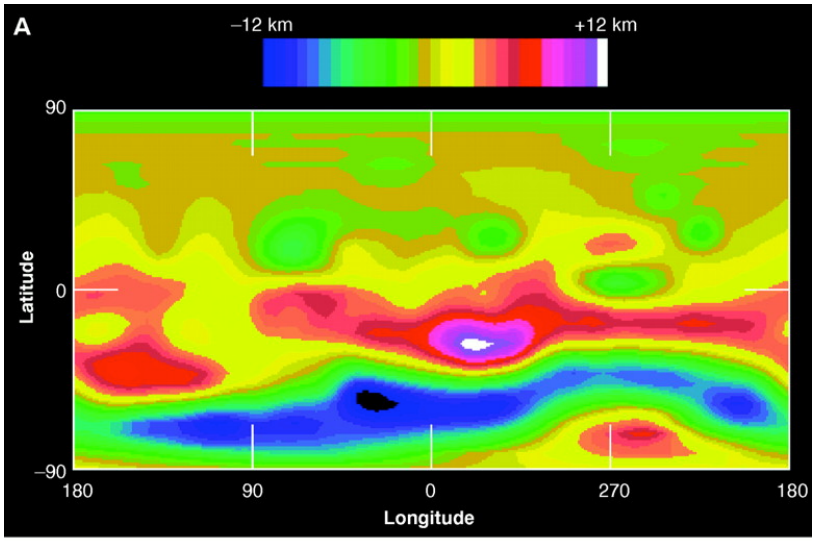
Pallasite

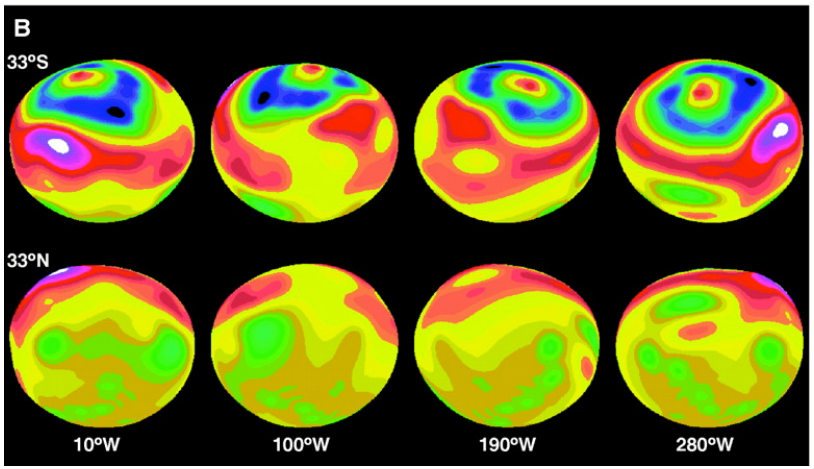
- **Some asteroids didn't heat up enough to differentiate**
  - **Meteorites of this unaltered material are called carbonaceous chondrites**
  - **High in carbon**
  - **Date from the very beginning of the solar system - 4.56 billion years ago**

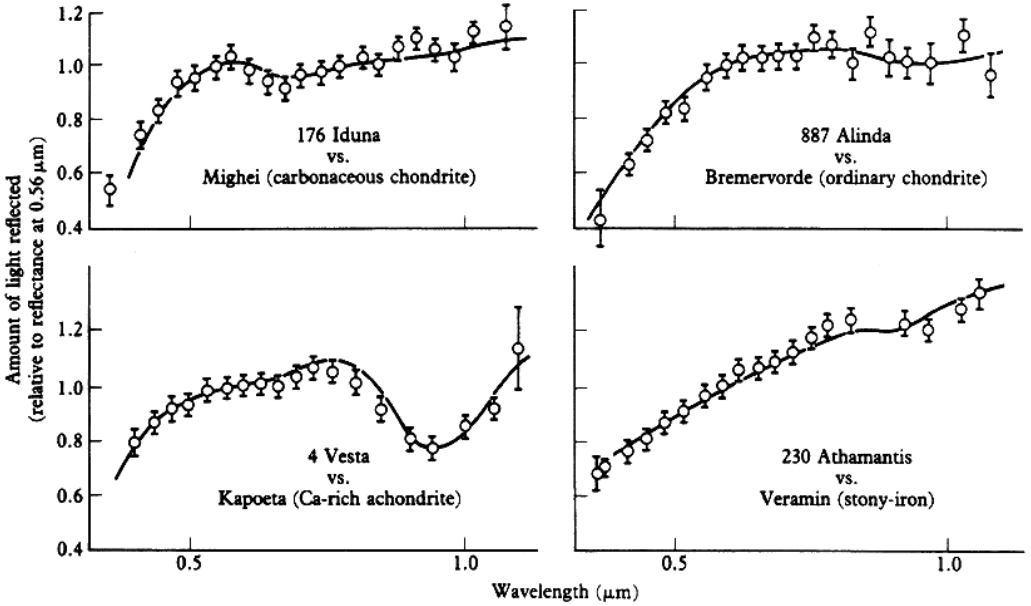
Figure 15-18
Universe, Eighth Edition

- **Some carbonaceous chondrites came from asteroids that heated up enough to melt rock but not ice**
  - **Water in the asteroid circulated among the rocks – altering their chemistry**

- **We can match some asteroids to groups of meteorites with their spectra**
  - **Certain groups of meteorites are matched to the asteroid Vesta**
  - **They show evidence for basalt flows on Vesta's surface**
  - **Volcanoes on Vesta? – We'll find out in a few years**







- **How do meteor showers work?**
  - **Asteroid/comet breaks up while orbiting**
  - **Debris is concentrated in a tube along the path of that orbit**
  - **Earth passes through these debris tubes**
  - **We see lots of these little fragments burn up in our atmosphere**
    - **Most of these are very small: ~sand-grained sized**

Table 15-1 Prominent Yearly Meteor Showers

Shower name	Date of maximum intensity*	Typical hourly rate	Average speed (km/s)	Radiant constellation
Quadrantids	January 3	40	40	Boötes
Lyrids	April 22	15	50	Lyra
Eta Aquarids	May 4	20	64	Aquarius
Delta Aquarids	July 30	20	40	Aquarius
Perseids	August 12	50	60	Perseus
Orionids	October 21	20	66	Orion
Taurids	November 4	15	30	Taurus
Leonids	November 16	15	70	Leo
Geminids	December 13	50	35	Gemini
Ursids	December 22	15	35	Ursa Minor

**The date of maximum intensity is the best time to observe a particular shower, although good displays can often be seen a day or two before or after the maximum. The typical hourly rate is given for an observer under optimum viewing conditions. The average speed refers to how fast the meteoroids are moving when they strike the atmosphere.*

Table 15-1
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In this lecture…

- Discovery of Asteroids
- The main asteroid belt – a failed planet
  - The Kirkwood gaps
  - Trojans
- Properties of Asteroids
  - Irregular shapes
  - Compositional zones in the asteroid belt
- Near-Earth asteroids – refugees from the main belt
- Meteorites
  - Different types and what they tell us
  - Meteor showers

Next: Special Topic

- Reading
  - Chapter 15 (section 1-6) to revise this lecture
  - Chapter ? for the next lecture