Also $\dot{P}$ due to emission of gravitational radiation.

$$\dot{P}_{orb} = -\frac{96}{5}\frac{G^3M^2\mu}{c^5}\left(\frac{4\pi^2}{GM}\right)^{4/3}\frac{f(e)}{P_{orb}^{5/3}}$$

$M = M_1 + M_2$, $\mu = M_1M_2/(M_1+M_2)$

$$f(e) = \left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)\left(1-e^2\right)^{-7/2}$$ e = eccentricity = 0.617...

Predicted + measured agree to 0.13%.

Even better - in 2003 double pulsar found - even more GR effects can be tested.

p. 705 Short-Hard Gamma Ray Bursts

<2s — merger of NS + BH or 2 NSs.

Hulse-Taylor system will be short-hard GRB in 300 million years.

Ch. 22 Minor Bodies of the Solar System p. 813

§22.3 Asteroids p. 830

Asteroids = minor planets

Vast majority in asteroid belt between Mars + Jupiter.

1st discovered = Ceres (1801)

Total # ~ 10^7, but combined mass ~ $5\times10^{-4}\,M_\oplus$

(Fig. 22.12) 243 Ida + moon Dactyl

= order of discovery: Ceres = 1 Ceres

p. 831 The Kirkwood Gaps in the Asteroid Belt

(Fig 22.13) Distribution of # of asteroids vs. semimajor axis a shows a-values with few or no asteroids (Kirkwood gaps) + a-values w/ overabundance.

These are due to orbital resonances w/ Jupiter.

Most prominent is at a = 3.3 AU, 2:1 resonance - asteroid w/ that a-value orbits 2X in Jupiter's orbital period, so every 2 orbits it gets a "kick" from Jupiter.

Also 2.5 AU → 3:1 resonance.

Some resonances are destabilizing (gaps) while others are stabilizing.

Since asteroids have various e's + orbital inclinations, there are not physical gaps, as there are in the rings of Saturn. (Fig. 22.14)

p. 831 The Trojan Asteroids

These are in Jupiter's orbit (1:1), either leading or trailing by 60°.

(Fig. 22.14 + 22.15)

In the frame orbiting w/ Jupiter, the L_4 + L_5 Lagrange points act as centers of attraction.

44b

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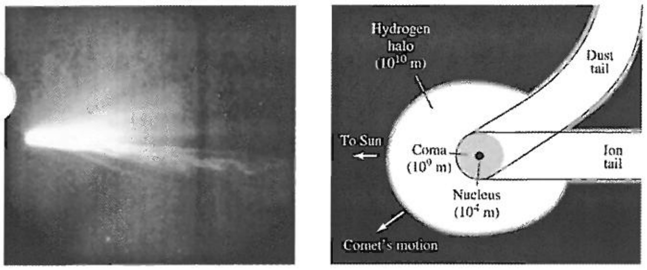

(a) (b)

Fig. 22.3 (a) Comet Halley with dust tail (curved) & ion tail (straight) in 1986. (b) Anatomy of a comet.

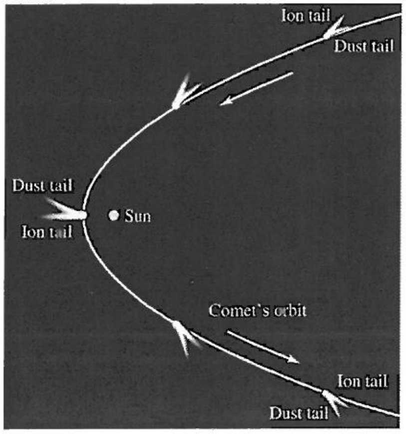

Fig. 22.5 The curved dust tail & the straight ion tail are always directed away from the Sun.

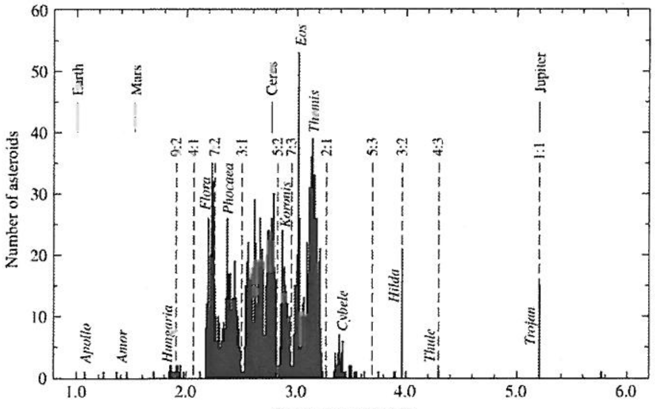

Fig. 22.13 The distribution of 1796 asteroids in the asteroid belt. Kirkwood gaps are evident at numerous resonance locations, & enhancements in the number of asteroids are apparent at other resonance locations.

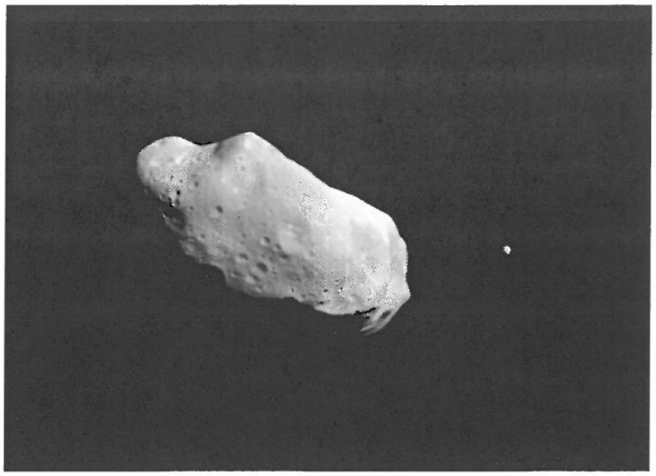

Fig. 22.12 243 Ida & its moon, Dactyl, as seen by Galileo spacecraft on Aug. 28, 1993 during its journey to Jupiter. Ida is 55 km long, & Dactyl is 1.6 km by 1.2 km.

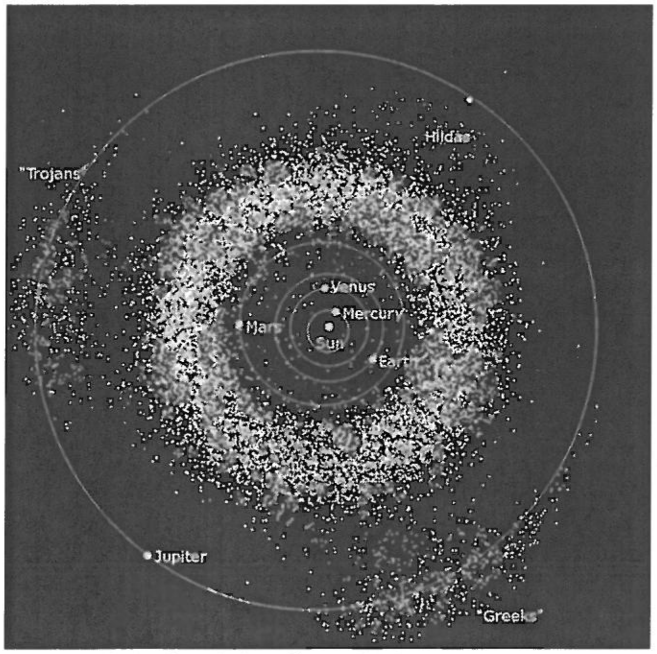

Fig. 22.14 Distribution of minor bodies in the inner Solar System.

44C

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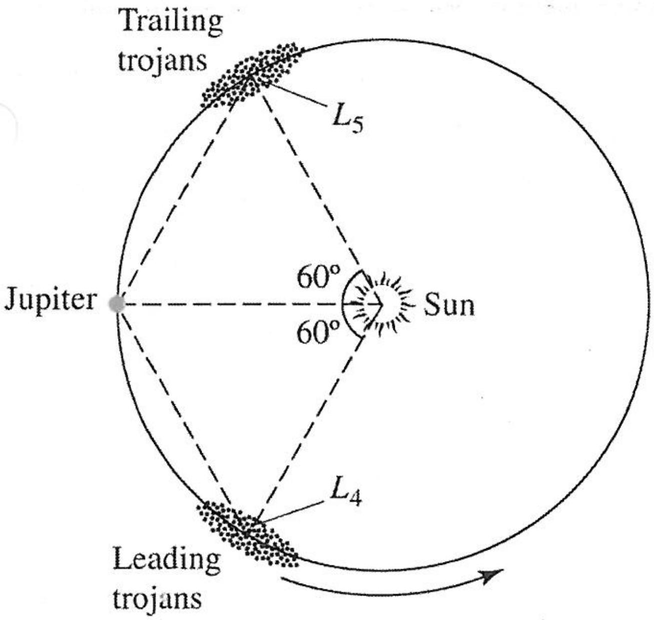

Fig. 22.15 Trojan asteroids are located in Jupiter's orbit, at 2 of the 5 Lagrangian points in the Sun-Jupiter system.

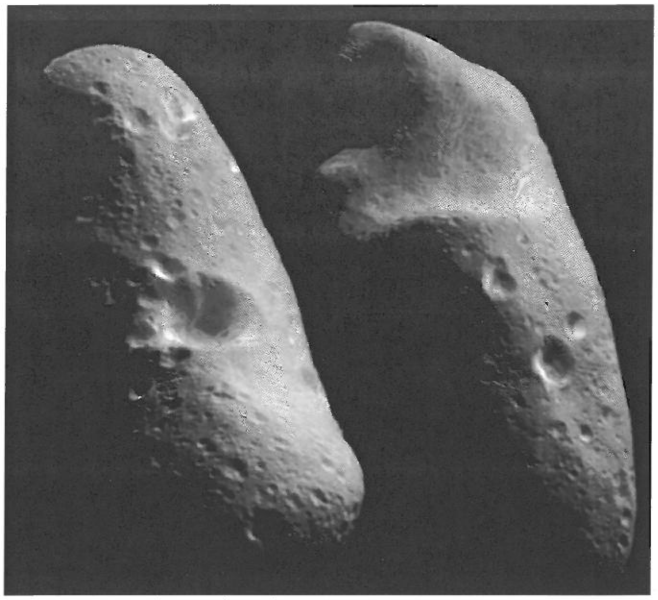

Fig. 22.16 Composite image of 2 hemispheres of 433 Eros as observed from orbit.

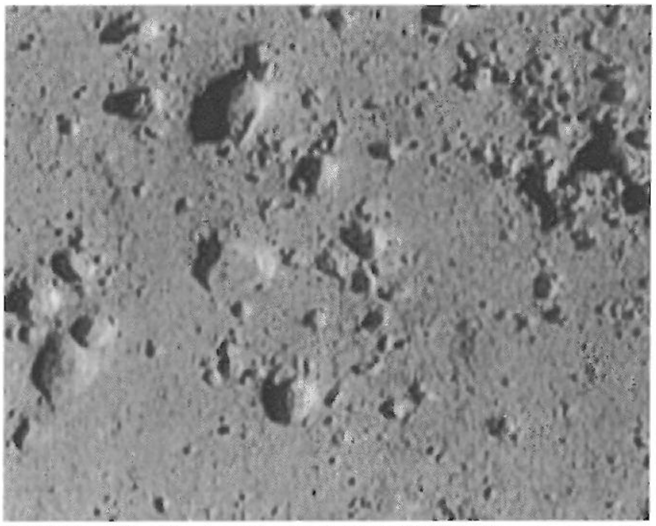

Fig. 22.17 The surface of Eros from 250 m altitude, Feb. 12, 2001 NEAR-Shoemaker spacecraft.

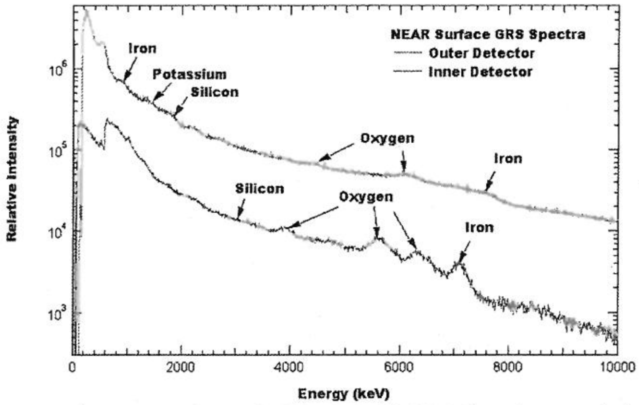

Fig. 22.18 The gamma-ray spectrum of 433 Eros obtained by NEAR-Shoemaker spacecraft after it landed on surface.

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p. 832 The Amors, Apollos, + Atens have orbits between Earth + Mars, crossing Earth's orbit near perihelion, or near aphelion respectively.

p. 833 Hirayama Families

>100 families of asteroids w/ nearly identical orbits.
Each family was probably originally of larger asteroid which suffered a collision.

p. 833 Rendezvousing w/ Asteroids

The Galileo spacecraft on its way to Jupiter flew by 951 Gaspra in 1991 + 243 Ida in 1993 (Ida + moon Dactyl are shown in Fig. 22.12)

Kepler's 3rd Law of Dactyl orbiting Ida ⇒ Ida mass = 3-4 × 10^{16} kg, ρ = 2200-2900 $\frac{kg}{m^3}$

Near Earth Asteroid Rendezvous (NEAR-Shoemaker) launched in 1996.
Went into orbit around 433 Eros on 2/14/2000 (Valentine's Day? Really?)
(Fig. 22.16) 33×8 km. Not designed as lander, but > 1 yr in orbit descended + landed at 1.6 $\frac{m}{s}$ (Fig. 22.17)
After it landed it measured γ-rays spectrum, found elements. (Fig. 22.18)

p. 835 Classes of Asteroids

Different colors, different compositions (Fig. 22.19)

p. 837 Internal Heating

There is evidence that the interiors of some asteroids were molten in the past.
People have made models involving radioactive decay, but the models have some problems.

Ch. 24 The Milky Way Galaxy

§24.1 Counting the Stars in the Sky

It's difficult to observe our Milky Way galaxy, due to dust + gas.

p875 Historical Models of the Milky Way Galaxy

In dark skies, anyone can see band of light, inclined ~60° w/ equator. (Fig. 24.1)
Galileo, w/ his telescope, saw that it is a huge collection of stars.
William Herschel (1738-1804) made map (Fig 24.2) assuming (1) all stars have a same intrinsic magnitude (2) number density in space ~ constant (3) no obscuration (4) he could see to edges of distribution.
Concluded that Sun near center.
Jacobus Kapteyn (1851-1922) model (Fig 24.3) used more quantitative methods, but also came up w/ distance estimates. Sun is actually ~8 kpc from galactic center.
1915-1919 Harlow Shapley estimated distances to globular clusters.

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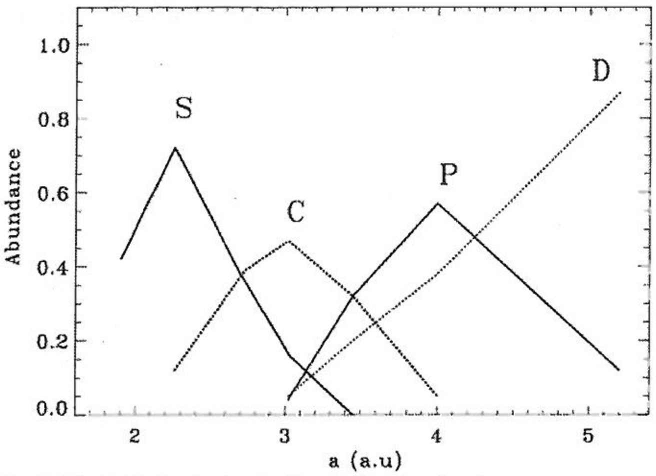

Fig. 22.19 The distribution of major asteroid types with distance from Sun.

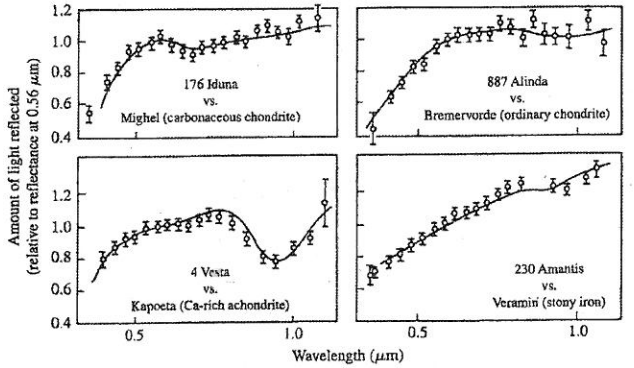

Fig. 22.21 Comparisons between the infrared spectra of asteroids (open circles with error bars) & meteorites (laboratory spectra = solid lines)

Shower	Approximate Date	Parent Body
Quadrantid	January 3	(unknown)
Lyrid	April 21	Comet 1861 I
Eta Aquarid	May 4	Comet Halley
Delta Aquarid	July 30	(unknown)
Perseid	August 11	Comet Swift-Tuttle
Draconid	October 9	Comet Giacobini-Zinner
Orioid	October 20	Comet Halley
Taurid	October 31	Comet Encke
Andromedid	November 14	Comet Biela
Leonid	November 16	Comet 1866 I
Geminid	December 13	Asteroid 3200 Phaeton

Table. 22.3 The Dates & Parent Bodies of Principal Meteor Showers

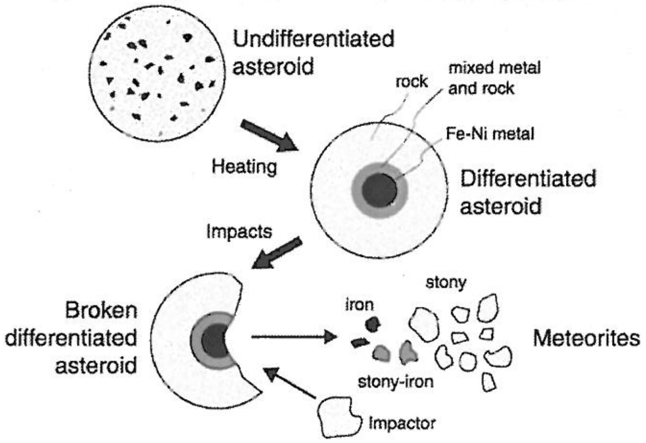

Figure: formation of meteorites from Northern Arizona U.: https://www.cefns.nau.edu/geology/naml/Meteorite/Book-GlossaryA.html

Fig. 22.22 50,000 year old Meteor Crater in Arizona is 1.2 km in diameter & 200 m deep. It was produced by an iron meteorite ~50 m in diameter.

22.4.1 (after p. 456) 2/27/18

§22.4 Meteorites p838

the Allende meteorite on 2/8/1969 exploded over Pueblito de Allende, Mexico, creating sonic booms + scattering pieces over a 50km×10km area.
streak of light produced by frictional heating.
Surfaces of pieces covered by fusion crusts, but interior unaffected.

p. 839 The Age + Composition of the Allende Meteorite

Radioactive dating w/ Pb isotopes → age = 4.566 ± 0.002 Gyr (compare to solar model age of Sun = 4.57 Gyr). So it is a primordial remnant of the early solar system.

CAI's + Chondrules

Too much detail, but the composition gives us clues to the temperature history of the early solar system.

p. 840 Carbonaceous + Ordinary Chondrites - skip

Chemically Differentiated Meteorites

Achondrites formed from molten stone.
Iron meteorites contain no stone (silicate) but may contain ≤20% nickel.
Of all meteorites hitting Earth, 96% are stone, 3% iron, 1% stony-iron.

p. 841 Sources of Meteorites

The vast majority of meteorites probably came from asteroids, due to collisions. Some large asteroids are probably gravitationally separated, so iron meteorites come from the core, stone from the surface, stony-iron from the interface, + some come from undifferentiated asteroids.
(Fig. meteorite formation from NAU).
Comparing spectra also shows that meteorites come from asteroids.
(Fig. 22.21)
We have also found meteorites that must have been knocked off the surfaces of the Moon + Mars.
As comets + asteroids orbit, debris gathers along their orbit, causing a meteor shower once a year if the Earth passes thru the orbit (Table 22.3 p. 842)
they are named after the constellations from which they appear to originate, which is the direction the Earth is moving at that date.

p. 842 A History of Collisions with Earth

Meteor crater in Arizona, 1.2 km diameter, 200 m deep. (Fig. 22.22)
Produced by 50m iron meteorite 50,000 years ago.

22.4.2 2/27/18

Then there was the Tunguska event in Siberia in 1908, which blew trees outwards in a 15 km radius. It was probabl caused by a stony meteorite exploded in the atmosphere, energy 5×10^{17} J = 12 Mtons TNT.

Several mass extinctions in Earth history could have been caused by asteroids, including one 65 Myr ago at the Cretaceous-Tertiary boundary that killed the dinosaurs + 70% of all species

It could have been a stony asteroid 6-10 km across, causing a crater 100-200 km in diameter.

The probability of an impact during our lifetime is ~1 in several thousand - we're working on detection + deflection.

p. 844 the Basic Building Blocks of Life

Some complex amino acids have been found in meteorites, indicating that they can form in space.

CH