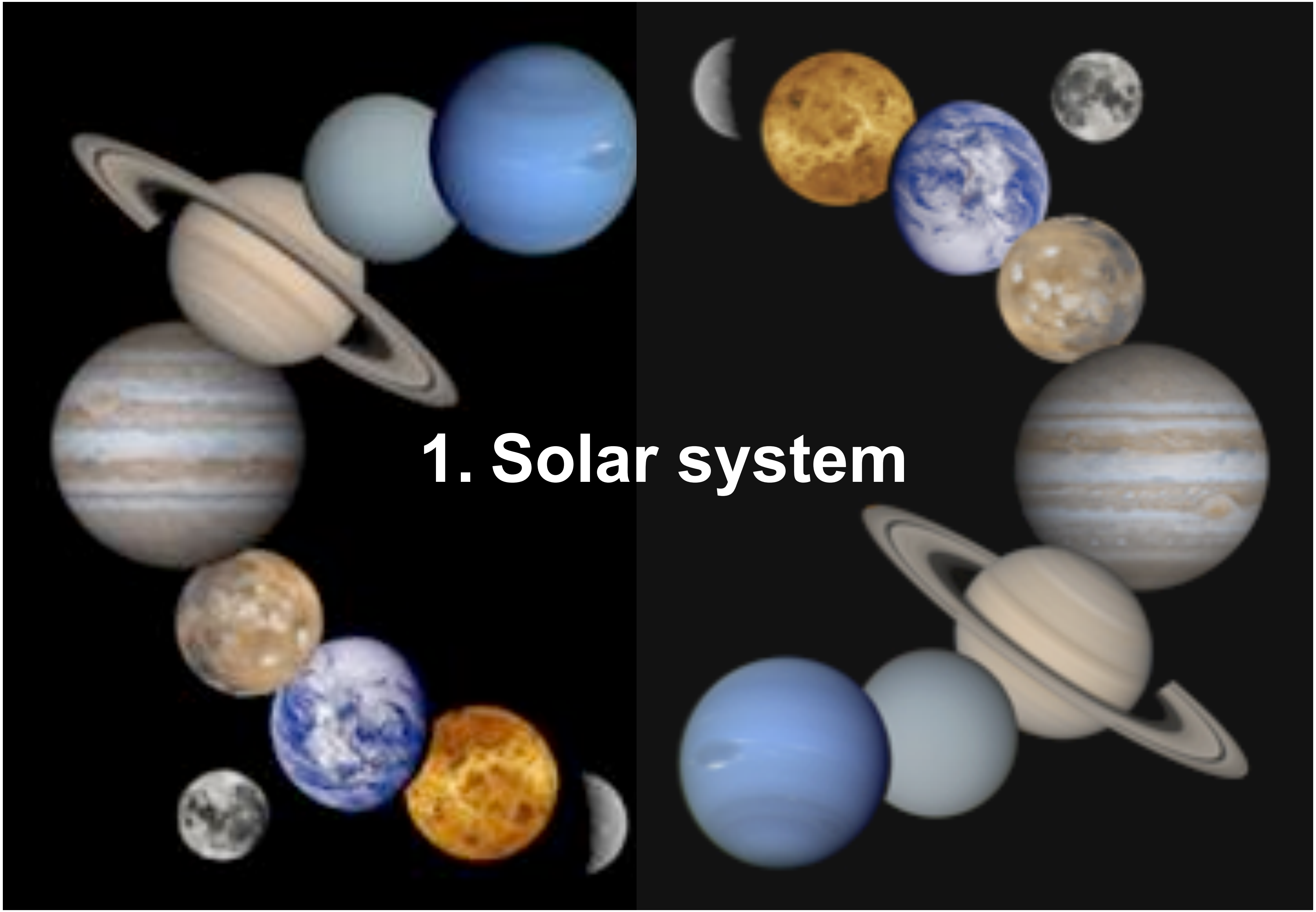
Planetary systems

Dr Mark Wyatt, Institute of Astronomy

1. Solar system	Wed 21 Jan, 2.30-3.30	Hoyle SLT
2. Planetary system dynamics	Tue 27 Jan, 2-3	Hoyle CR
3. Extrasolar planets	Wed 28 Jan, 2.3-3.30	Hoyle CR
4. Planet formation	Tue 3 Feb, 2-3	Hoyle SLT
5. Protoplanetary disks	Wed 4 Feb, 2.30-3.30	Hoyle SLT
6. Debris disk observations	Tue 10 Feb, 2-3	Hoyle CR
7. Debris disk theory	Wed 11 Feb, 2.30-3.30	Hoyle SLT
8. Debris disk application	?	?

Graduate lecture course, 20 Jan-11 Feb 2009

1. Solar system



Why study the solar system?

- Still many outstanding questions
  - Formation?
  - Evolution?
  - New members?
  - Development of life?

- Testbed for physics of planetary systems
  - Application to extrasolar systems
  - Context: how unique are we?

- Impact on extragalactic observations/cosmology
  - Thermal emission from zodiacal cloud (Maris et al. 2006; Babich et al. 2007)
  - Fast moving objects
  - Pioneer anomaly testing GR

Components of the solar system

- The Sun
  - Mass/luminosity
  - Solar Wind/Magnetic field

- Planets and their moons and ring systems
  - Terrestrial planets: Mercury, Venus, Earth, Mars
  - Jovian planets: Jupiter, Saturn, Uranus, Neptune
  - Dwarf planets: Pluto (Ceres, Eris)

- Minor planets
  - Asteroids: Asteroid Belt, Trojans, Near Earth Asteroids
  - Comets: Kuiper Belt, Oort Cloud

- Dust
  - Zodiacal Cloud

The Sun - mass

- Vital stats:
  - Mass = 1.989 x 10^{30} kg
  - Radius = 6.95 x 10^{8} m
  - Mean density = 1410 kg/m^3

- Definition of the solar system is the material gravitationally bound to the Sun

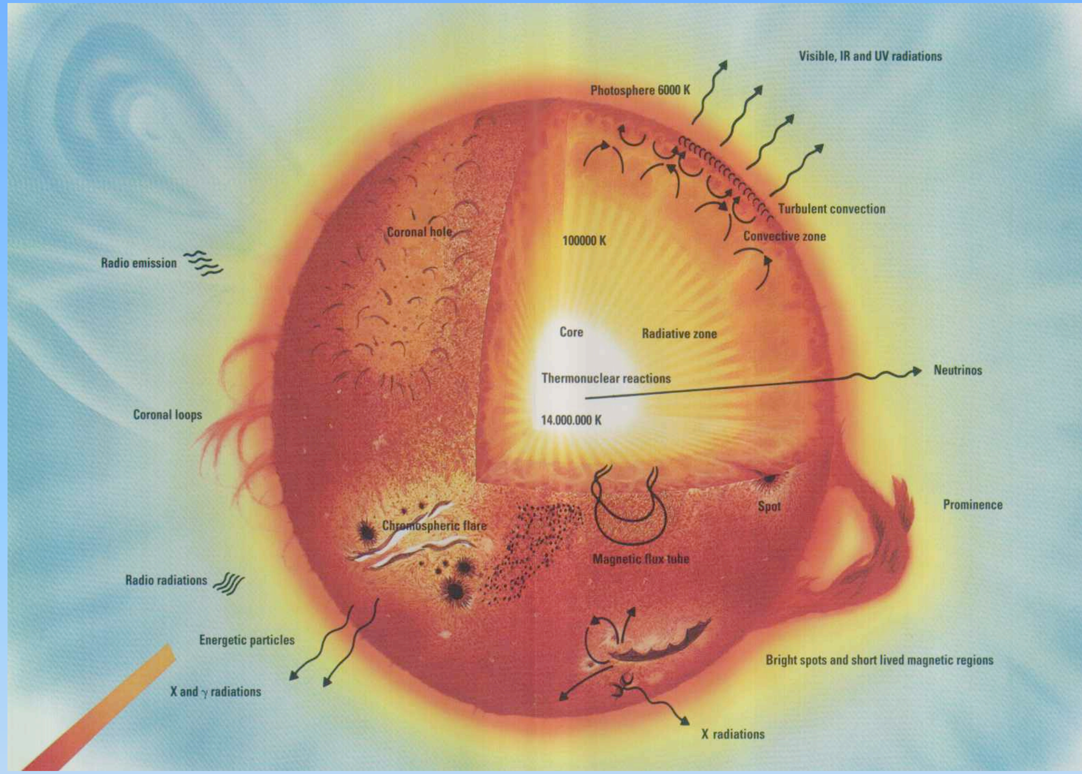
- Everything orbits the Sun on elliptical orbits with orbital periods of

  $t_{per} = a^{1.5}$ years

  where a=semimajor axis in AU

- The Sun's influence extends out to ~100,000 AU (~0.5 pc), outside which galactic tides strip material from the solar system

The Sun - structure



- Core: like all stars on the main sequence, the Sun produces energy by burning H in its core

- Convective zone: that energy is carried to the surface through a radiative ($<0.85R_{sun}$) and convective ($0.85\text{-}1R_{sun}$) zone

- Photosphere: is the visible surface of the Sun which has a temperature of ~5785 K, although sunspots have lower temperatures of ~4000 K

- Chromosphere (CaII and Hα emission, faculae, flares)

- Corona (prominences, loops, origin of solar wind)

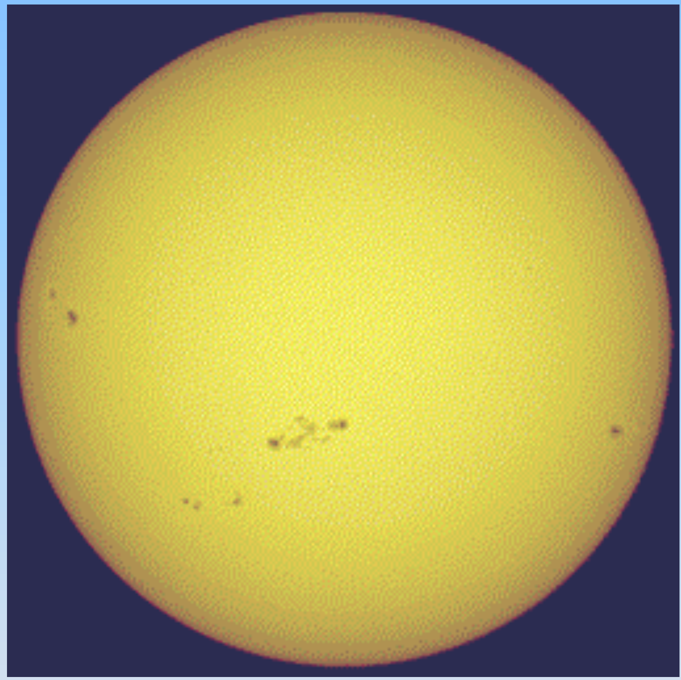
The Sun – rotation

- The Sun's rotation period on the surface varies from 25 days at the equator to 36 days at the poles

- Below the convective zone rotation is ~27 days

- Rotation axis is 7.25^0 from the ecliptic (which is the plane of Earth's orbit)

- This rotation is just a small fraction of the angular momentum of the solar system (most of which is in the gas giant planets)



The Sun – luminosity/spectrum

- The most simple expression for the solar spectrum would be a black body at a temperature T_{eff}

- This implies a luminosity of

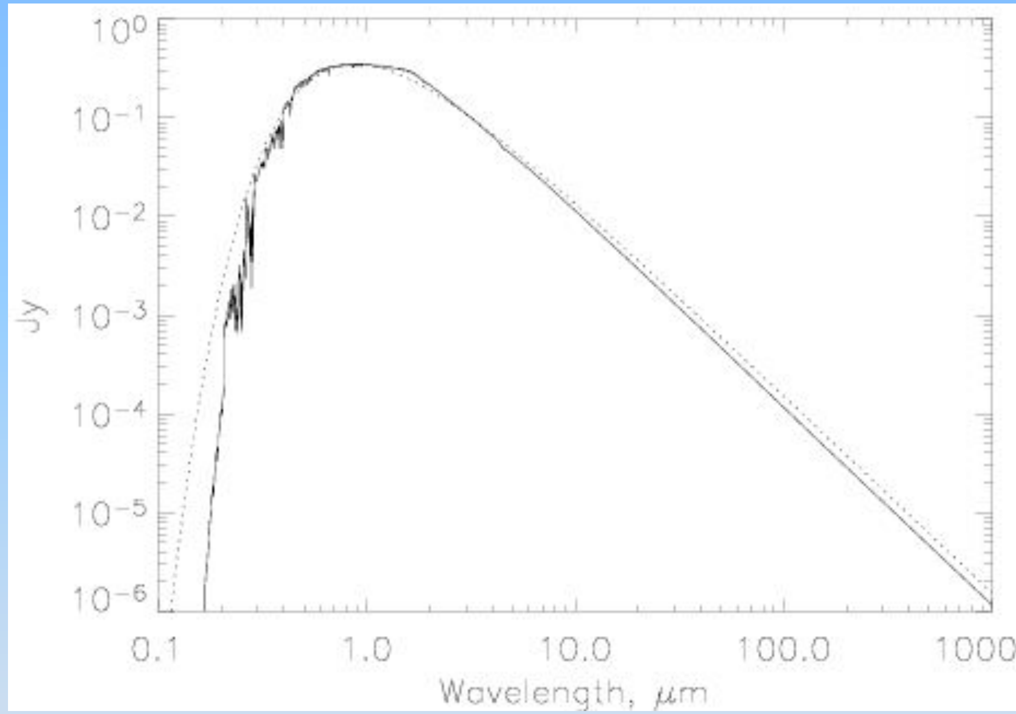
  $L_{sun} = 4\pi R_{sun}^2 \, \sigma \, T_{eff}^4$

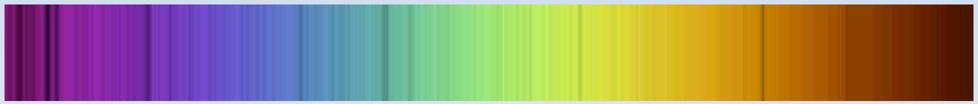
  where $\sigma = 5.67 \times 10^{-8}\ JK^{-4}m^{-2}s^{-1}$

  $L_{sun} = 3.826 \times 10^{26}$ W

- But the true spectrum contains lots of lines and tells us about solar composition (and temperature)

- Models such as Kurucz model atmospheres can be used to work out the spectrum

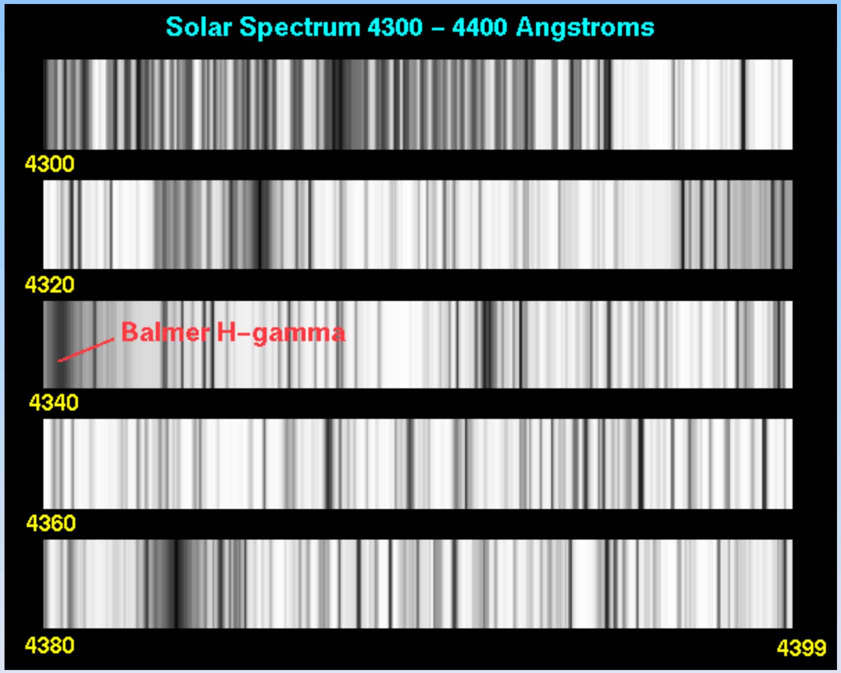




The Sun – composition

- The Sun is composed mainly of Hydrogen and Helium. By mass (measured from spectra of photosphere, but thought representative of all but core, e.g., from neutrino flux, Gonzalez 2006):

H	71.0%
He	27.1%
O	0.97%
C	0.40%
N	0.096%
Si	0.099%
Mg	0.076%
Ne	0.058%
Fe	0.14%
S	0.040%
Other	0.0015%



- This compares well with the composition of the rest of the material in the solar system (meteorites and terrestrial planets)

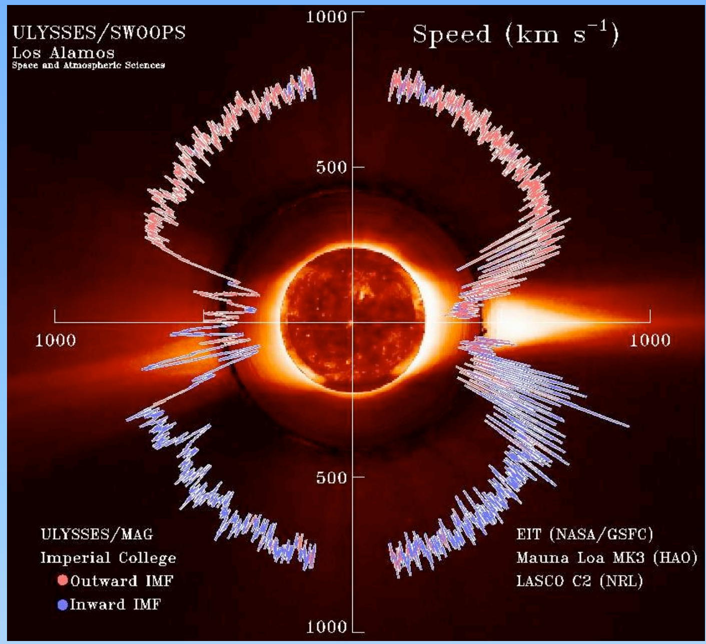
The Sun – solar wind

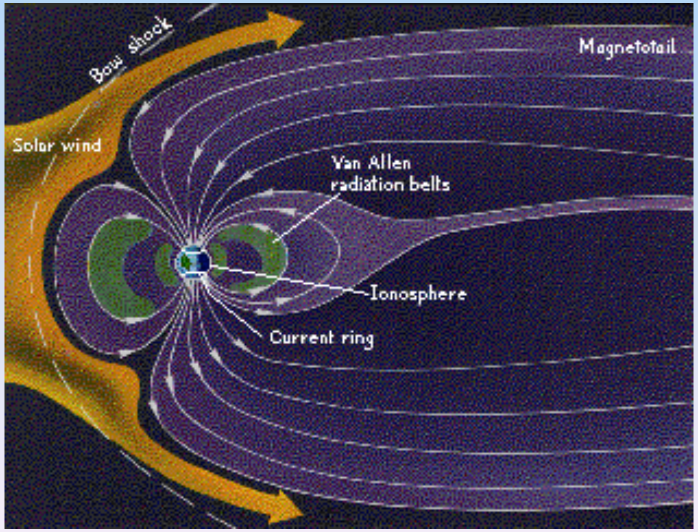
- First discovered because comet ion tails always point away from the Sun; caused by fast moving ions in the corona which escape the Sun's gravitational field

- It has a slow component (300-500km/s) at the equator (<15^0) and fast component (700-800km/s) at higher latitudes; at 1AU mean density is 7×10^6 protons/m^3 ($v \sim$ const, so $\rho \propto r^{-2}$); neutral, roughly solar composition

- Interaction of charged particles with planet magnetospheres and atmospheres -> aurorae borealis

- Solar wind interacts with the interstellar medium at the heliopause



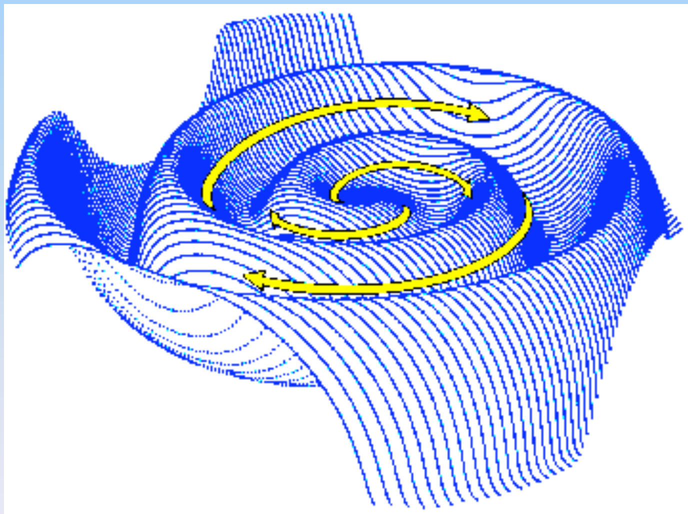


The Sun – magnetic field

• Spectroscopy of Zeeman splitting of lines shows sunspots are regions of strong magnetic fields

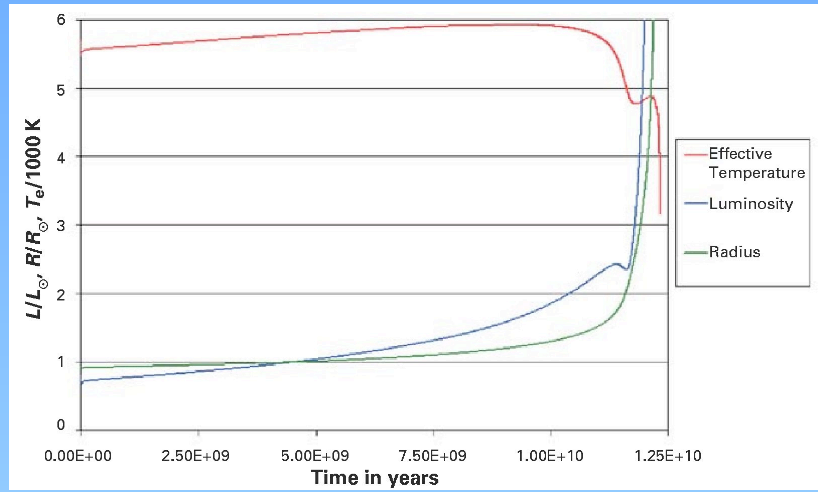
• Solar magnetic field is carried into space by solar wind to form interplanetary magnetic field (IMF)

• Solar wind flow is radially away from the Sun, but because of solar rotation the open field line is anchored to the Sun so that the IMF has a spiral pattern (Parker 1958); at the Earth the IMF is at 45^0 to the radial direction, and is weak $B \sim 5 \times 10^{-5}$ G



• The field is a split magnetic monopole with inward and outward pointing field lines in different hemispheres and a neutral current sheet (sector boundaries)

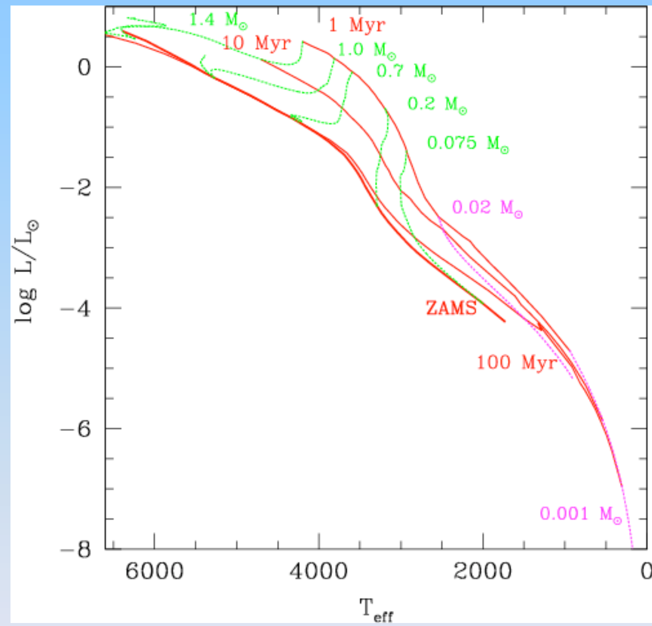
The Sun – evolution



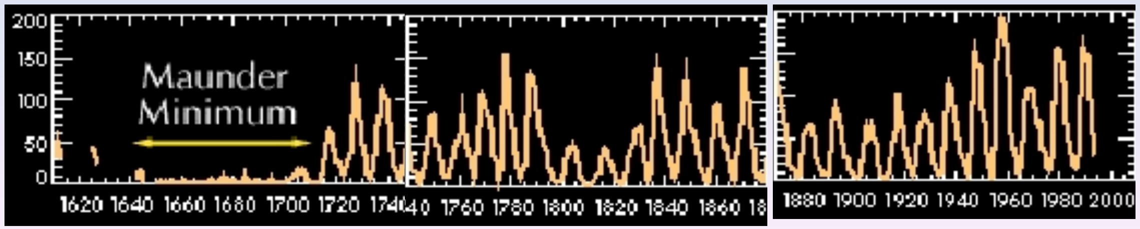
The Sun has an age of 4.5 Gyr, while its main sequence lifetime is ~10Gyr

Long term evolution:

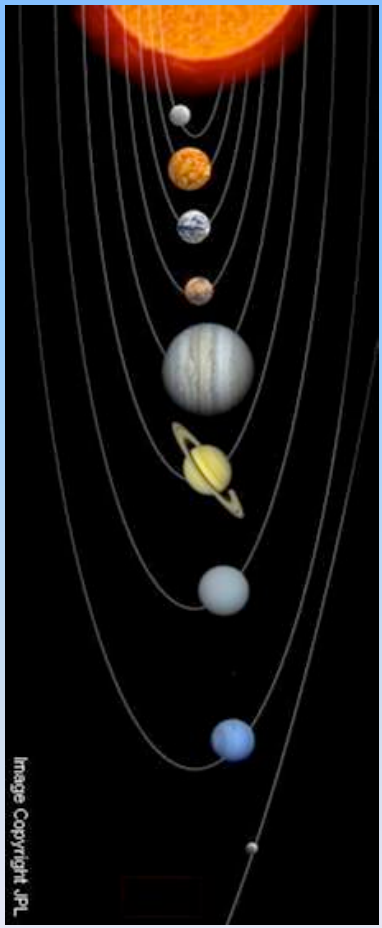
- Pre-main sequence evolution (PMS evolutionary tracks to zero age main sequence)
- Main sequence evolution (slight luminosity increase)
- Post-main sequence evolution (Red Giant branch)



Short timescale variations due to, e.g., sunspot cycles: 11 years + Maunder minimum (1640-1710) when no sunspots and cold temperature on Earth; more prominences and flares at solar maximum



The planets – overview/mass



	Mass	Distance
Mercury	$0.06\ M_{earth}$	0.39 AU
Venus	$0.82\ M_{earth}$	0.72 AU
Earth	$1.0\ M_{earth}$	1.0 AU
Mars	$0.11\ M_{earth}$	1.5 AU
Jupiter	$318\ M_{earth}$	5.2 AU
Saturn	$98\ M_{earth}$	9.5 AU
Uranus	$15\ M_{earth}$	19.2 AU
Neptune	$17\ M_{earth}$	30.1 AU
Pluto	$0.002\ M_{earth}$	39.5 AU

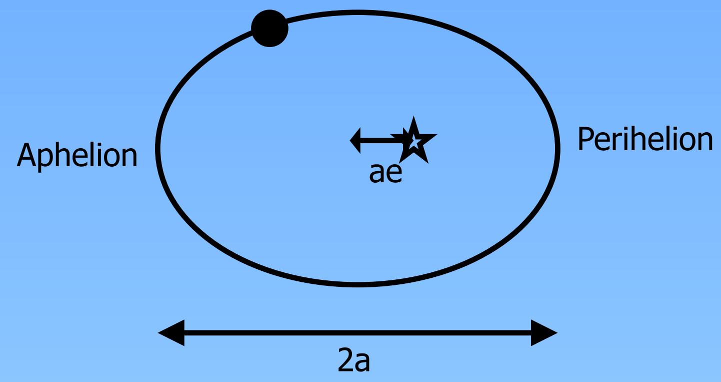
Terrestrial planets (Mercury, Venus, Earth, Mars)

Jovian planets (Jupiter, Saturn, Uranus, Neptune)

Dwarf planet (Pluto)

$1\ M_{earth} = 6 \times 10^{24}$ kg $= 3\times10^{-6}\ M_{sun}$, 1 AU $= 1.5 \times 10^{11}$ m

The planets - orbits



Three things I will say about orbits:

- Semimajor axis, a ($t_{per}=a^{1.5}$)
- Eccentricity, e
- Inclination, I

	a, AU	e	I, deg
Mercury	0.39	0.206	7.0
Venus	0.72	0.007	3.4
Earth	1.0	0.017	0.0
Mars	1.5	0.093	1.9
Jupiter	5.2	0.048	1.3
Saturn	9.5	0.054	2.5
Uranus	19.2	0.047	0.8
Neptune	30.1	0.009	1.8
Pluto	39.5	0.249	17.1

- Evenly spaced -> Titius-Bode's law $a=0.4+0.3(2^i)$, predicted Ceres (1801) and Uranus (1781)

- La Grande Inequalite (JS near 5:2 resonance) and NP in 3:2 resonance

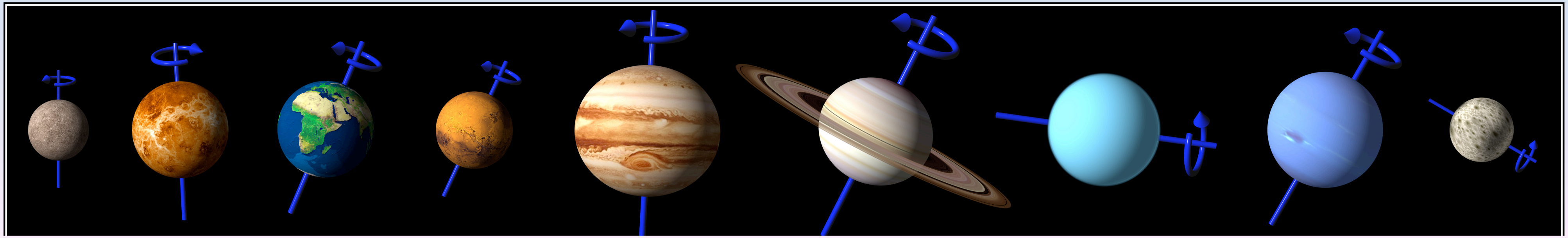
- All orbit in the same direction, in the same plane on roughly circular orbits

- Except Pluto, and possibly Mercury; high e of JS also important for formation/evolution

The planets - rotation

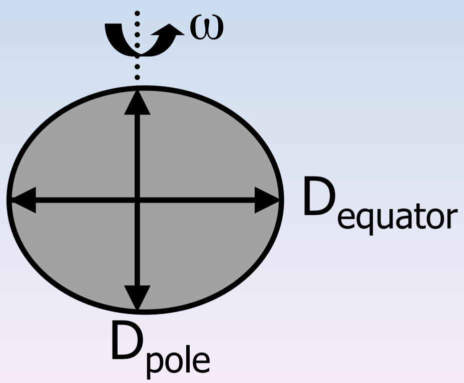
	T_{per}, yrs	P_{rot}, hrs	Obliquity
Mercury	0.241	1407.5	0.1^0
Venus	0.615	5832.5	177.4^0
Earth	1.00	23.9345	23.45^0
Mars	1.88	24.623	25.19^0
Jupiter	11.86	9.925	3.12^0
Saturn	29.46	10.656	26.73^0
Uranus	84.00	17.24	97.86^0
Neptune	164.80	16.11	29.56^0
Pluto	247.7	153.29	119.6^0

- Mercury is in a 3:2 spin-orbit resonance, probably despun by solar tides
- Venus, Uranus and Pluto have retrograde rotation, possibly as result of collision with proto-planet during formation (Canup 2005; Parisi et al. 2008)
- NB obliquity is measured relative to orbital plane rather than ecliptic



The planets – shapes

- To zero-th order planets are spherical
- To first order they are oblate spheroids, where oblateness is defined as $f=(D_{equator}-D_{pole})/D_{equator}$
- The origin of the oblateness is in rotation as well tides from their satellites (and the Sun)
- The response of a planet to tides tells you about its internal structure



	Oblateness, $(D_{eq}-D_p)/D_{eq}$
Mercury	0.000
Venus	0.000
Earth	0.0034
Mars	0.0065
Jupiter	0.0649
Saturn	0.098
Uranus	0.023
Neptune	0.017
Pluto	0.0

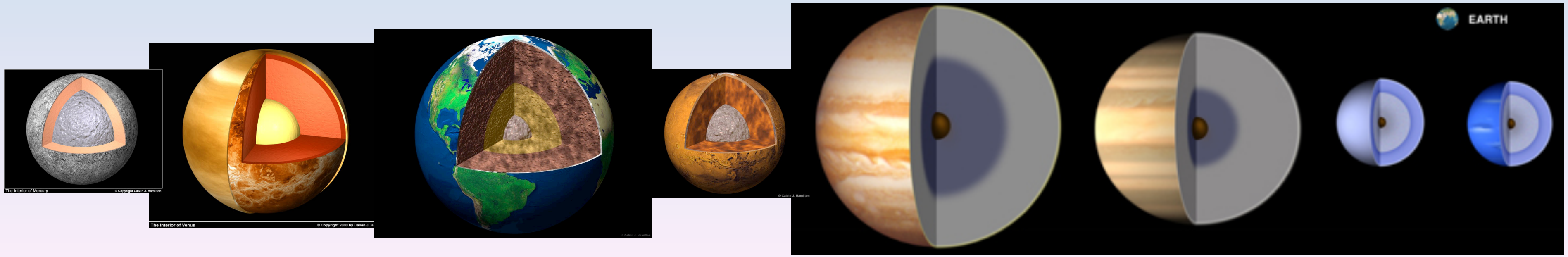
The planets – internal structure

Terrestrial planets:
- iron core, rocky mantle, crust (differentiated in formation)
- Mercury's high density -> large iron core (to $0.75R_{pl}$), perhaps caused by massive impact (Asphaug et al. 2006)

Jovian planets:
- rocky/icy (liquid) core and metallic/molecular hydrogen (JS) or mantle of ices and H/He/CH_4 gas (UN)
- mass of Jupiter's core is model dependent $0\text{-}11M_{earth}$, but Saturn's core does exist $9\text{-}22M_{earth}$ (Sauron & Guillot 2004)

Pluto: rocky core, ice mantle, layer of frozen methane, nitrogen and carbon monoxide

	Density, kg/m^3
Mercury	5427
Venus	5204
Earth	5515
Mars	3933
Jupiter	1326
Saturn	687
Uranus	1318
Neptune	1638
Pluto	2060



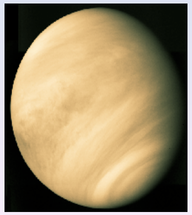
The planets - atmospheres

• Mercury and Mars have very tenuous atmospheres due to their low gravity (thermal velocity>escape velocity), leading to large night/day temperature variations

• Pluto's tenuous atmosphere comes from surface ices which evaporate when Pluto approaches Sun ($r_{pluto}<r_{neptune}$ 1979-1999)

• Clouds increase albedo (i.e., reflection of sunlight) and are made of NH_3 ice on Saturn and crystal CH_4 on Uranus

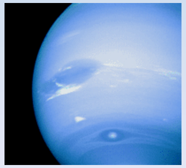
• Permanent covering of sulphuric acid clouds on Venus; but dense atmosphere ($P_{venus}=90P_{earth}$) leads to greenhouse effect



	Albedo	T, K	Composition
Mercury	5.6%	100-700	He, H
Venus	72%	737	CO_2, N_2, SO_2
Earth	38.5%	290	N_2, O_2, Ar, H_2O
Mars	16%	184-242	CO_2, N_2, Ar, O_2
Jupiter	70%	165	H_2, He, CH_4
Saturn	75%	134	H_2, He, CH_4
Uranus	90%	76	H_2, He, CH_4
Neptune	82%	72	H_2, He, CH_4
Pluto	14.5%	50	CH_4, N_2

• CH_4 above clouds on Uranus causes blue colour (and on Neptune)

• Storms on Jupiter (great red spot) and Neptune (great dark spot), and 500m/s winds at Saturn's equator

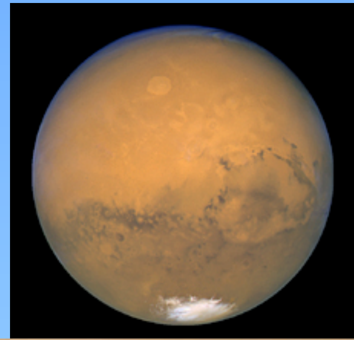


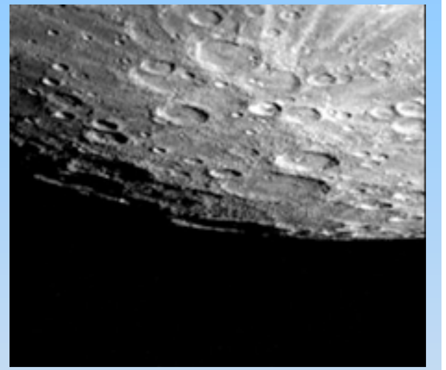
• Dense parallel bands of clouds on Jupiter and Saturn

The planets – surface features

Jovian planets have liquid surfaces, but for terrestrial planets + Pluto:

- **Polar ice caps**: all (except Venus)
- **Craters**: Mercury heavily, no small (<2km) craters on Venus, few on Earth due to plate tectonics, on both Mars and Pluto
- **Water**: none Venus and Mercury, oceans on Earth, water channels on Mars
- **Topological**: mountains on Earth (8km), Mars (Olympus Mons 27km), valleys (Mars Valles Marineris)
- **Volcanoes**: Earth (active), Venus, Mars
- **Plate tectonics**: on Earth wipes out craters; Venus strong crust; Mars thick crust
- **Wind**: wind erosion on Venus, dust storms on Mars
- **Other**: large dark spots on Pluto near equator, Venus surface young 300-500 Myr

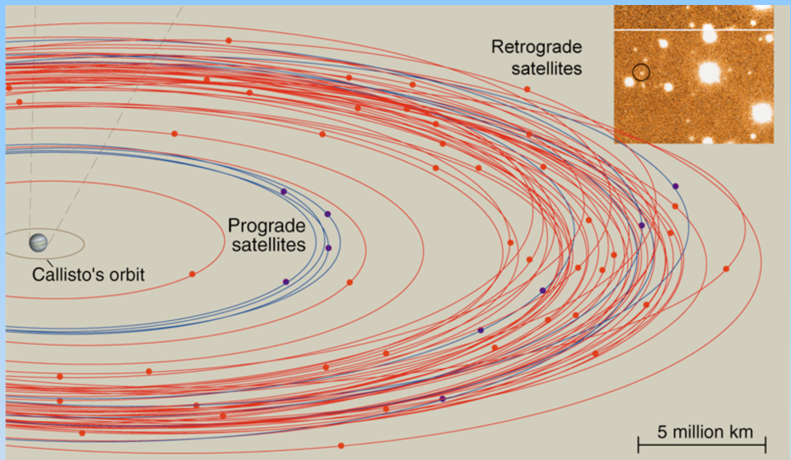




The planets - satellites

• Terrestrial planets (and Pluto) have <3 moons

• Jovian planets have >13 moons which fall into two categories: regular and irregular (Jewitt & Haghighipour 2007)



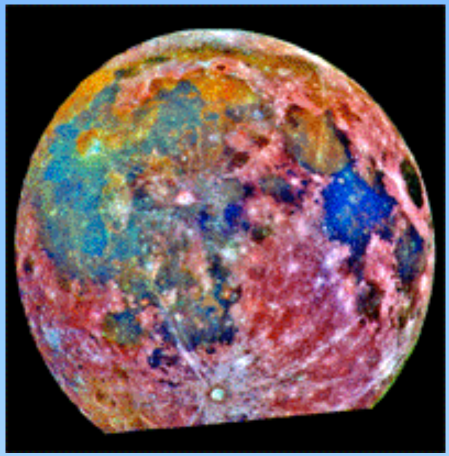
	Satellite count
Mercury	0
Venus	0
Earth	1
Mars	2
Jupiter	63
Saturn	47
Uranus	27
Neptune	13
Pluto	3

Origin of satellites:
• circumplanetary disk during planet formation (Estrada & Mosqueira 2006)
• circumplanetary disk following massive collision
• captured minor planets
• fragments of planet from collision

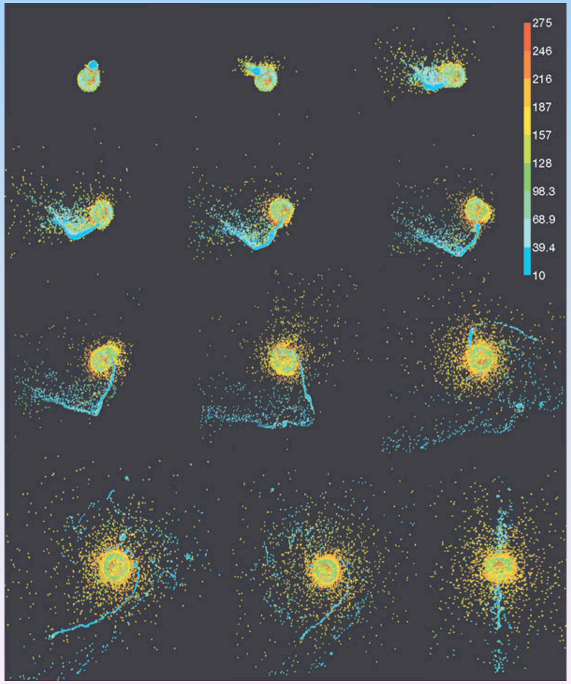
Also interesting because:
• Some are planets in their own right
• Testbed of planetary system dynamics
• Used to tell us about interior of planets

Planetary satellites – Earth's Moon

Vital stats:
Mass = 0.012 M_{earth}, density = 3.3 g/cm^3
Interior: mostly rocky
Surface: magma oceans; dusty regolith 2-20m deep; craters
Atmosphere: none
Orbit: a=384,400 km, e=0.05, I=5.2^o
Spin: rotation period = orbtial period = 27.3 days (Wisdom 2006)
Synchronous rotation -> Moon keeps same face to us

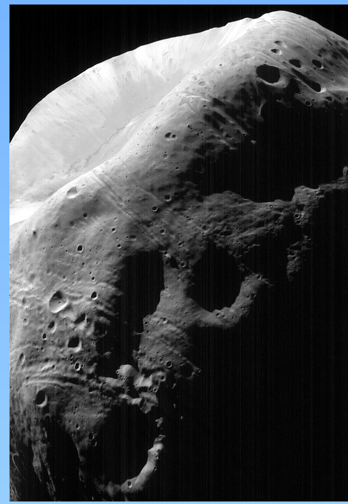


Origin:collision with Mars-sized impactor when Earth was 70% of its current size (Canup & Asphaug 2001) forming a circumplanetary disk out of which the Moon accreted in ~1month. Work still ongoing on models (e.g., Wada et al. 06).



Evidence for a period of **Late Heavy Bombardment**
• spike in lunar rock resetting ages
• spike in ages of lunar impact melts
• impact basins Nectaris (3.9-3.92Gyr) and Orientale (3.82Gyr) imply quick decline (half life 50Myr)
• cratering on Mercury, Mars and Galilean satellites support LHB, but equivocally

Planetary satellites - Mars



Mars has two satellites, both discovered in 1877:

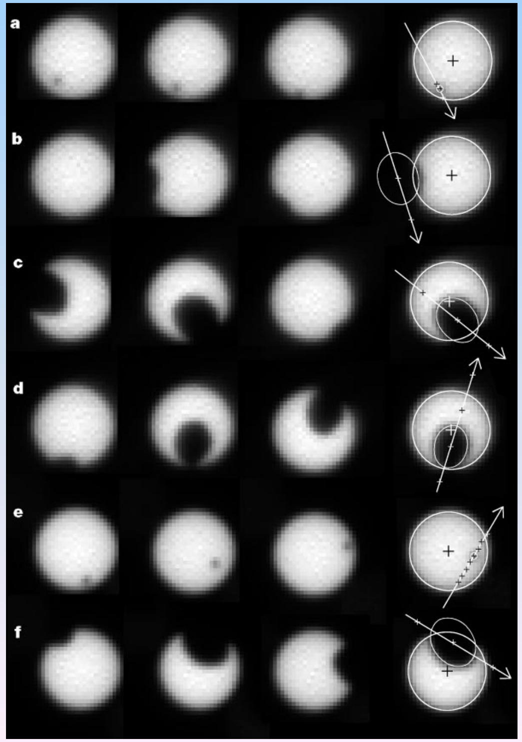
- Phobos: D=10 km, a=9,380 km, synchronous rotation, $i=0.01^0$
- Deimos: D=6 km, a=23,500 km, synchronous rotation, $i=0.92^0$

Phobos will spiral into Mars in a few Myr, but Deimos will not

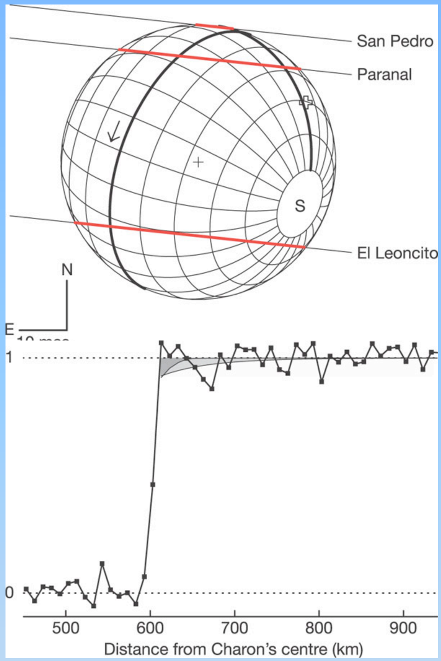
Origin is thought to be capture of asteroids, but the origin of the equatorial orbits is a mystery.

Singer (2003) suggests a capture of a more massive asteroid which disintegrated, the largest fragments of which already fell onto Mars.

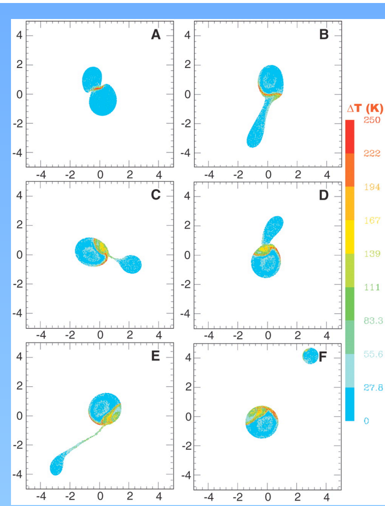
Transits of Phobos and Deimos across the Sun as observed from Mars (Bell et al. 2005) will constrain orbital evolution due to tides and so internal structure of Mars

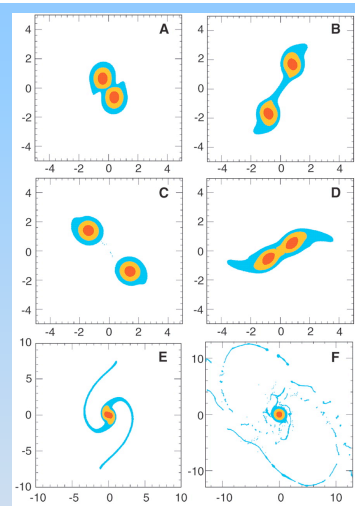


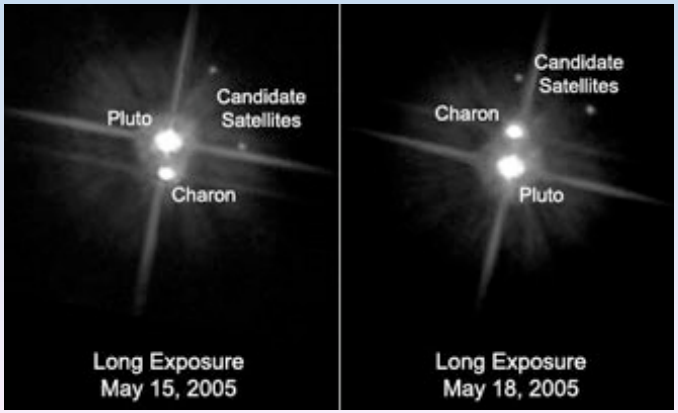
Planetary satellites - Pluto

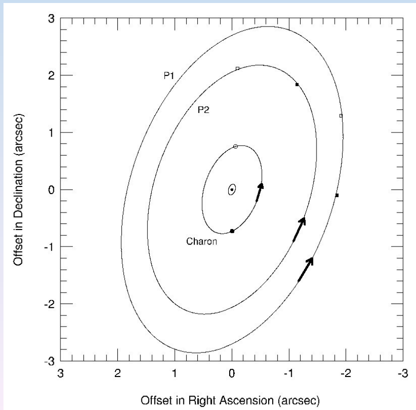


Charon, discovered in 1978
• Diameter = 1207 km (half that of Pluto)
• Distance = 19,600 km
• Surface = covered in dirty water ice
• Mutually synchronous rotation with Pluto means they keep same face to each other
• No atmosphere (Sicardy et al. 2006)
• Believed to have formed in collision (Canup 2005), though two scenarios still possible





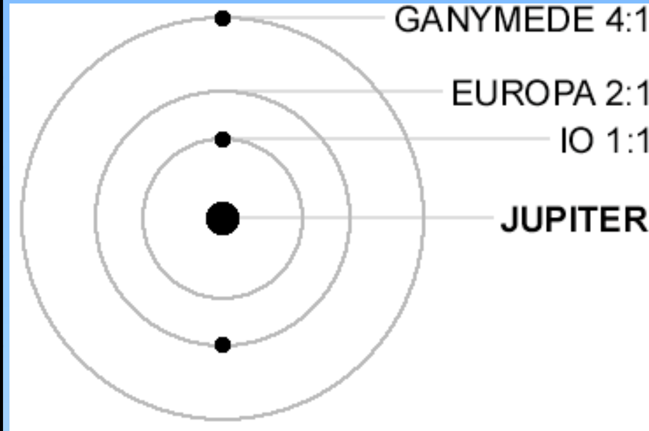




New satellites discovered (Weaver et al. 2006): P1 and P2 which are 60-165km diameter 6:4:1 orbital period ratio (Buie et al. 2006; Lee & Peale 2006) believed formed in collision with KBO (Stern 2006)

Planetary satellites – Galilean Moons

	Distance	Mass
Io	422,000 km	0.015 M_{earth}
Europa	671,000 km	0.008 M_{earth}
Ganymede	1,070,000 km	0.025 M_{earth}
Callisto	1,883,000 km	0.018 M_{earth}



Io: strong vulcanism caused by 100 m tides from Jupiter (synchronous rotation) and orbital resonance with Europa; sulphur gives it a red/yellow colour

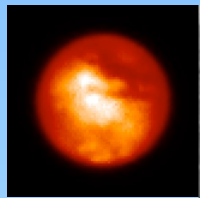
Europa: cracked icy surface; liquid water under surface; heated by tides; no craters

Ganymede: cratered; rock and ice; maybe water; largest moon in Solar System, and larger than Mercury and Pluto

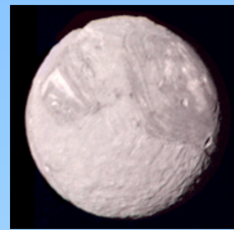
Callisto: most heavily cratered; rock and ice

Planetary satellites – Saturn/Uranus/ Neptune regular moons

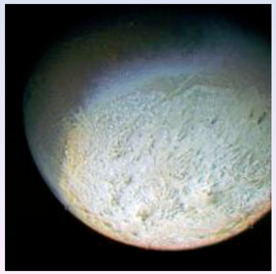
Titan: discovered 1655 by Huygens
- Mass = 0.022 M_{earth} (i.e., > $M_{Mercury}$)
- Distance = 1,221,850 km
- Temperature = -178 C
- Atmosphere = dense, hazy; N_2, CH_4, some organics; clouds
- Surface features = 75% liquid ethane or methane oceans? (West et al. 2005); continents
- Rotation = synchronous with Saturn (16 days)
- Catpured core? (Prentice 2006)



Uranus: including Miranda with 20 km deep fault canyons, terraced layers



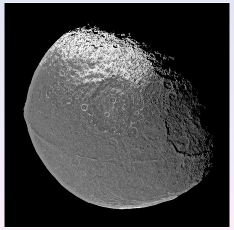
Neptune: biggest is Triton with retrograde orbit which will spiral onto Neptune in a few Myr (captured moon, Agnor & Hamilton 2006); ice volcanoes spewing nitrogen and methane which snows back onto surface



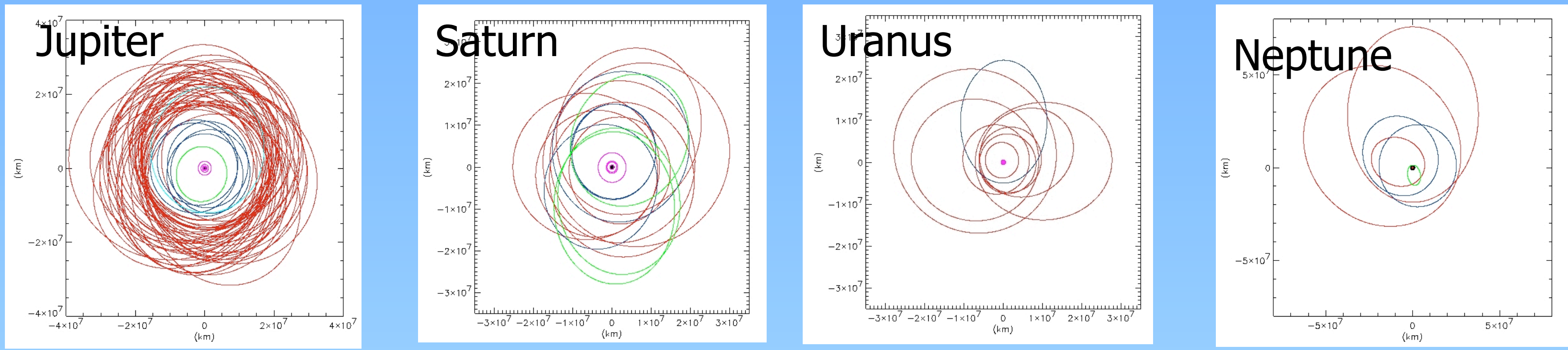
Enceladus: particularly shiny (water ice/snow)

Mimas: huge crater 1/3xdiameter (392 km)

Iapetus: dark material, equatorial ridge



Planetary satellites – Irregular satellites



Of Jupiter's 63 satellites the majority are irregulars and rather than large satellites on circular coplanar close-in orbits, these are smaller (D=2-200km) satellites on eccentric (e to 0.4) inclined (I to 50^0) more often retrograde orbits at large distance (>$7x10^9$m for Jupiter)

Wide field deep imagers -> large numbers -> find dynamical families and that number of irregulars measured to given diameter constant for all planets (Jewitt & Sheppard 2005)

Origin in capture from passing asteroids/comets, perhaps during formation, although also in collisions (e.g., Nereid and S/2002 N1 around Neptune, Grav et al. 2004; Nesvorny et al. 2004 -> collisions with protoplanetary disk) and dynamics -> captured objects released in 100 orbits, Holman et al. (2004)

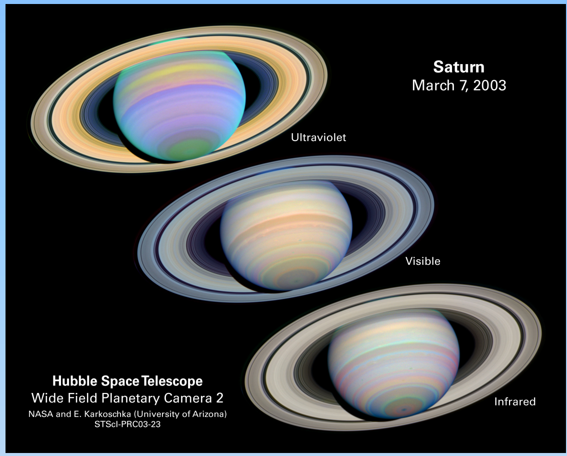
Follow-up involves, e.g., spectroscopy to determine origin (e.g., Vilas et al. 2006) showing that Jupiter irregulars from AB, others mostly from KB

The planets – ring systems

None of the terrestrial planets (or Pluto) have ring systems but all of the Jovian planets do

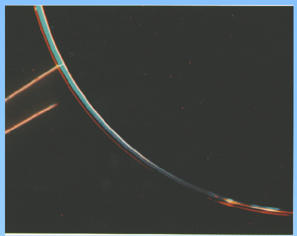
Although recently Pluto suggested to form dust rings sporadically when KBOs collide with its moons (Stern 2006)

And there's a large amount of space debris in orbit around the Earth…

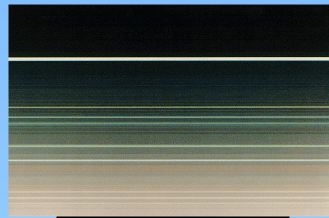


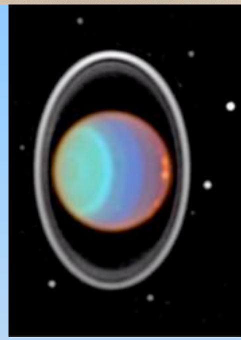
They are interesting because:
- circumplanetary disk processes similar to circumstellar disk processes
- test of planetary system dynamics
- finding satellites
- origin and evolution

Planetary rings – Jovian rings overview

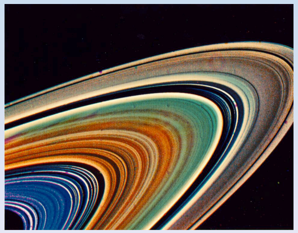


Jupiter: rings discovered in 1979 by Voyager 1; comprised of dust <10 μm in diameter; Main=122,800 km (30 km thick); Halo=Extends from main ring to Jupiter; Gossamer= >129,000 km; debris from smaller satellites; affected by magnetic forces

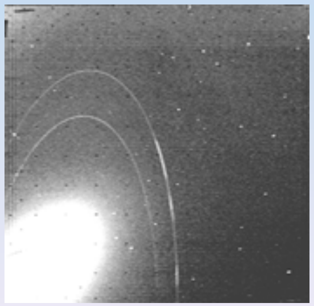




Uranus: 11 rings discovered in 1977; very narrow, eccentric and inclined; shepherded by satellites; dark, carbon particles up to m in size; self-gravitational effects



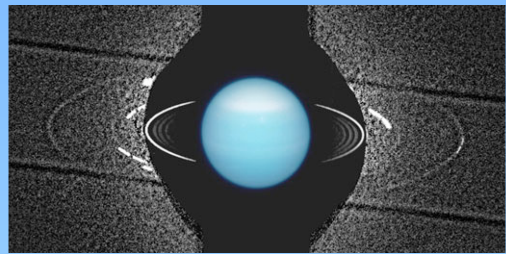
Saturn: rings discovered in 1610 by Galileo; but Huygens in 1651 interpreted as rings; Cassini in 1675 discovered the first gap in the rings; Voyager found composed of ice few μm to 10s of m; evidence for shepherding moons; A-G rings; braided rings

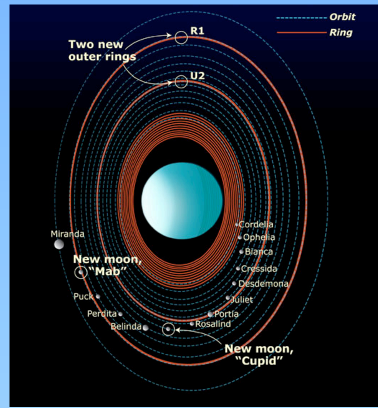


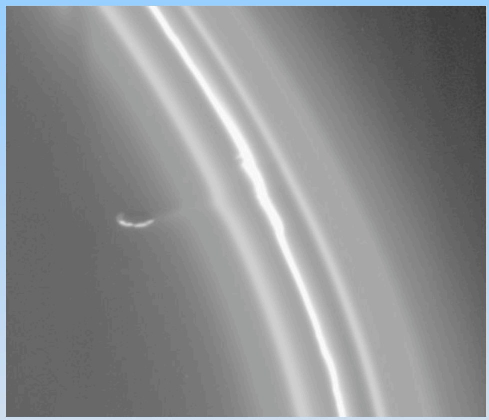
Neptune: several narrow rings; including Adams ring made up of incomplete arcs and clumps from satellite interactions

Planetary rings – recent results

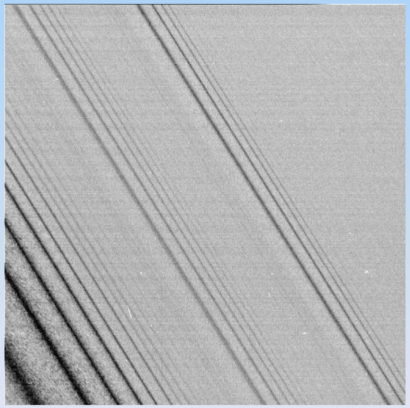
Discovery of two new rings around Uranus (Showalter et al. 2006): R1 replenished by impacts onto moon Mab; past disruption of moon origin for R2; chaos -> moons unstable and will collide in few Myr -> youthful dynamic system







Discovery of single one-armed spiral structure in Saturn's F ring (Charnoz et al. 2005): not shepherded by Pandora and Prometheus as thought, but disrupted (Prometheus steals material) and S/2004 S6 moonlet discovered by Cassini also involved



Density wave structure in Saturn's rings as expected theoretically from perturbations from Janus, Epimetheus, and Pandora (Murray et al. 2004)

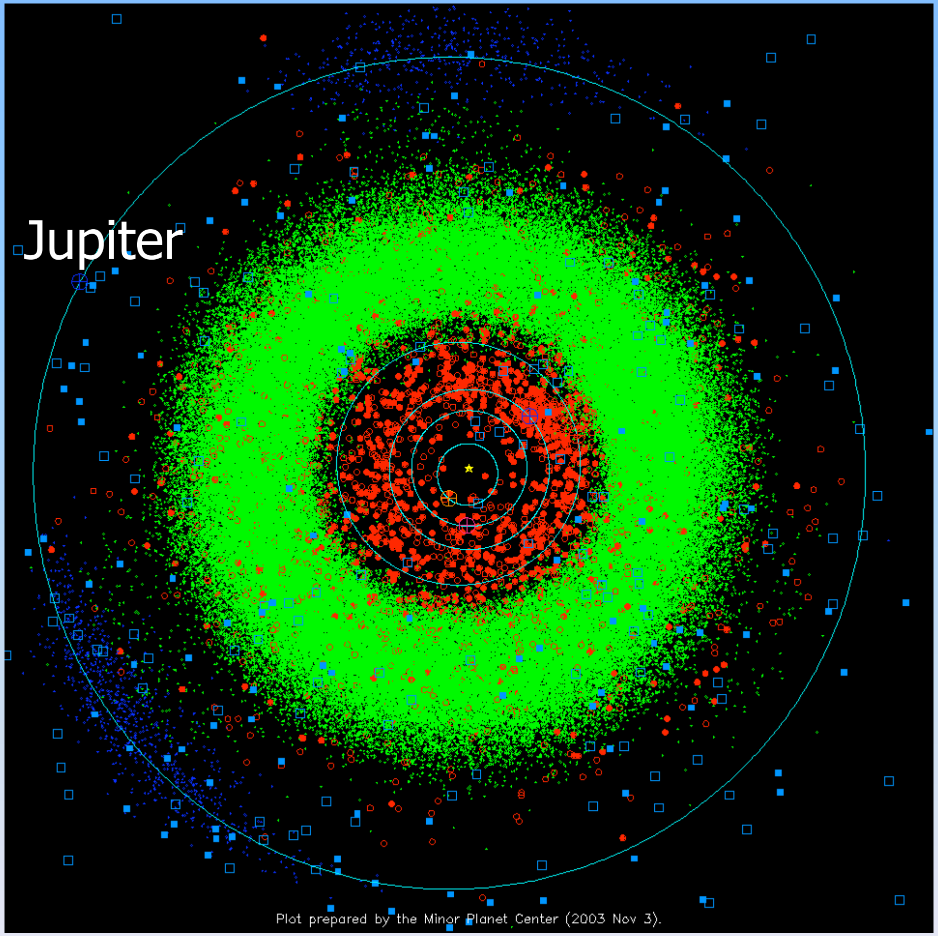
Minor planets in the inner solar sytem

• The Asteroid Belt is the belt of rocky asteroids orbiting 2-3.5 AU from the Sun (green)

• Some of asteroids in the Earth region (Near Earth Asteroids in red)

• Another family of asteroids are the Jupiter Trojans at ± 60^o from Jupiter

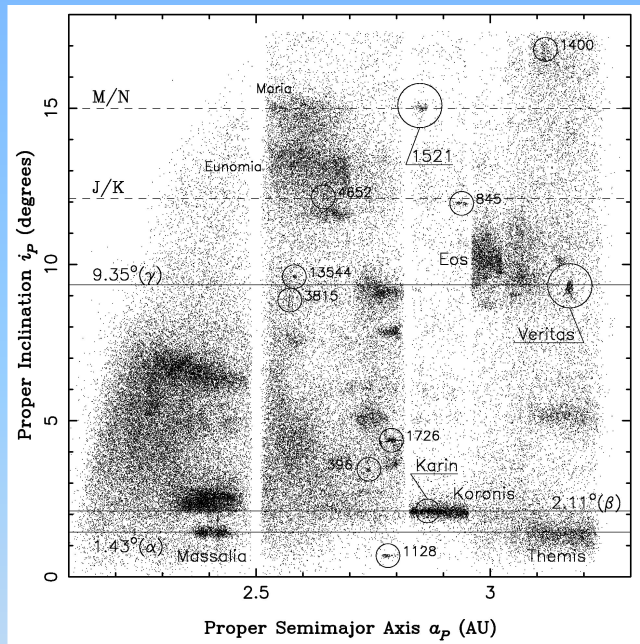
• There are 20,000 numbered asteroids



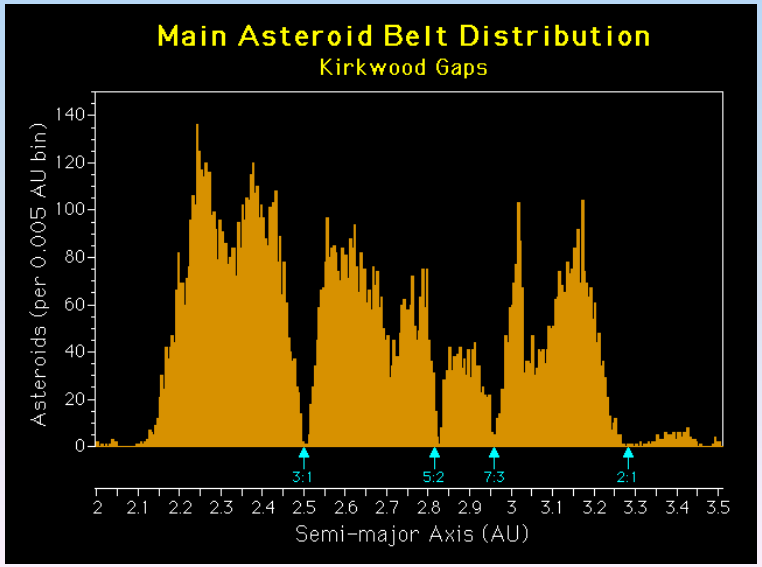
The Inner Solar System

Asteroids – orbit distribution

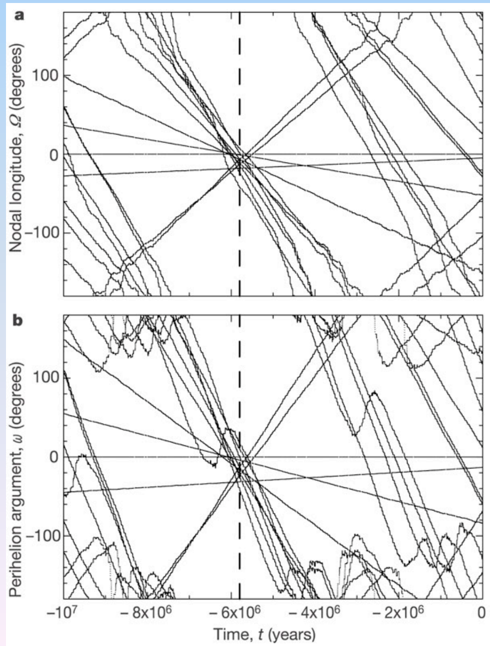
Kirkwood in 1886 noticed there are gaps in the distribution of asteroids; these are caused by gravitational perturbations from Jupiter



More recently evidence of families created when medium-sized asteroids collided just a few Myr ago (Nesvorny et al. 2002; 2003) and even 0.1Myr (Nesvorny et al. 2006)



Also clustering in the orbits of the asteroids (Hirayma 1918): families of asteroids created in the break-up Gyr-ago of much larger asteroids (Eos, Themis, Koronis, Massalia, Flora…)



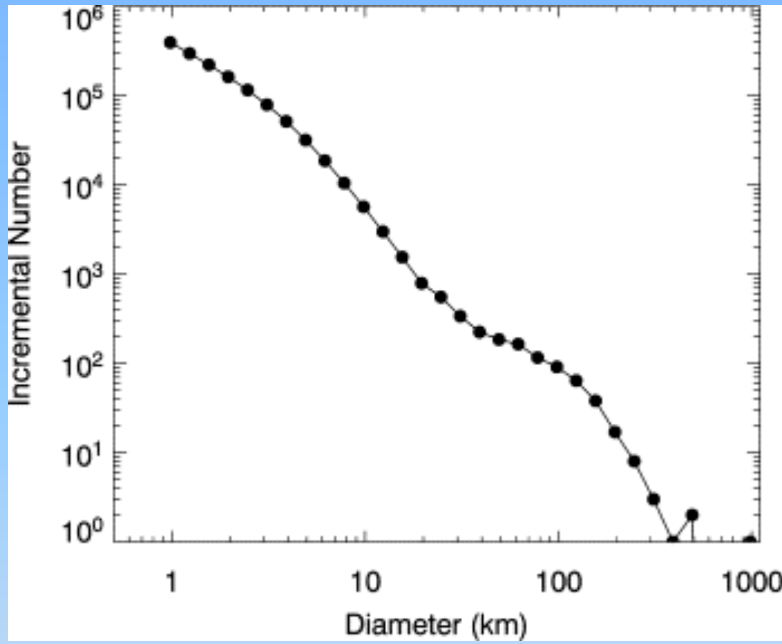
Asteroids – size distribution

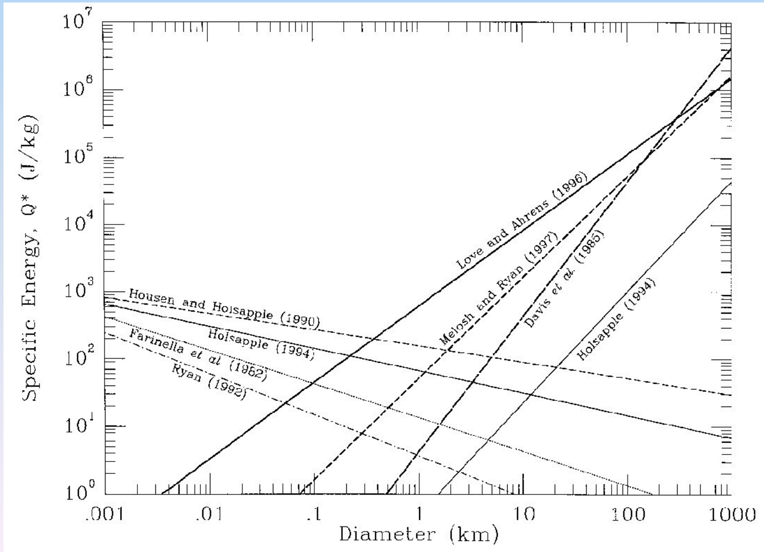
- The size distribution is converted from a magnitude distribution by making assumptions about asteroid albedo

- The distribution is very similar to that expected in an infinite collisional cascade (Tanaka et al. 1996):
  $n(D) \propto D^{2-3q}$ where q=11/6

- But there is a wave in the size distribution

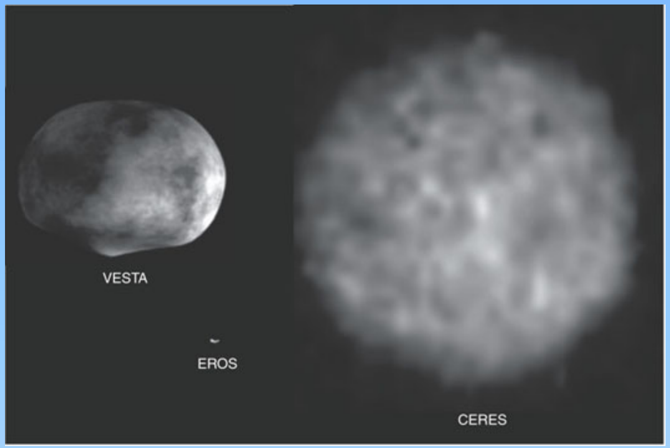
- This could be caused by the transition from strength to gravity scaling (Durda et al. 1998), but may be the fossilized size distribution of AB early evolution (Bottke et al. 2005)





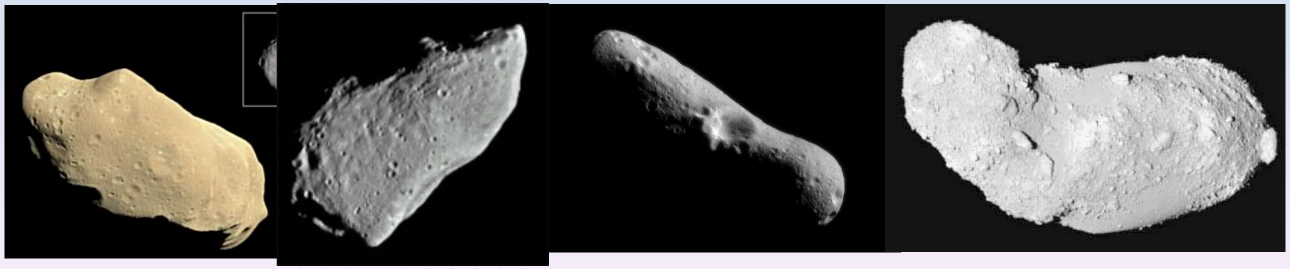
Asteroids – physical properties

• Largest asteroid is Ceres at 940 km diameter



• Vesta is the only known differentiated asteroid with a basaltic crust, ultramafic mantle and metal core (Keil 2002); its intact crust implies no catastrophic collisions setting constraints on AB evolution; origin of melting unknown (^{26}Al?)

• Asteroids are NOT spherical: Galileo spacecraft flew past Gaspra and Ida in 1991 and 1993; NEAR landed on the asteroid EROS in 2001; surface regolith (dusty layer); Hayabusa recent orbit around 500m asteroid Itokawa



Asteroid composition:
- C-type (carbonaceous)
  - 75%, solar composition
  - albedo=0.03-0.09
- S-type (silicaceous)
  - 17%, Fe/Mg silicates
  - albedo=0.1-0.22
- M-type (metallic)
  - 8%, metallic
  - albedo=0.1-0.18

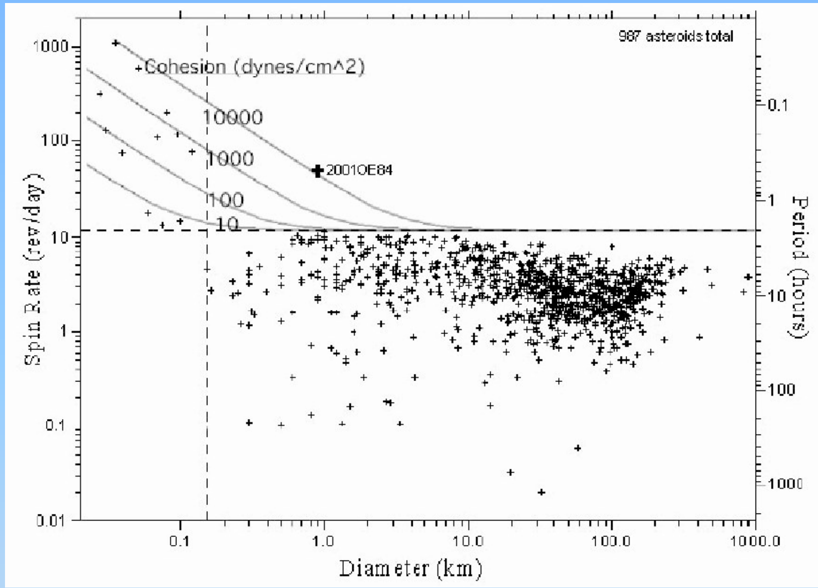
Asteroids – spin and rubble piles

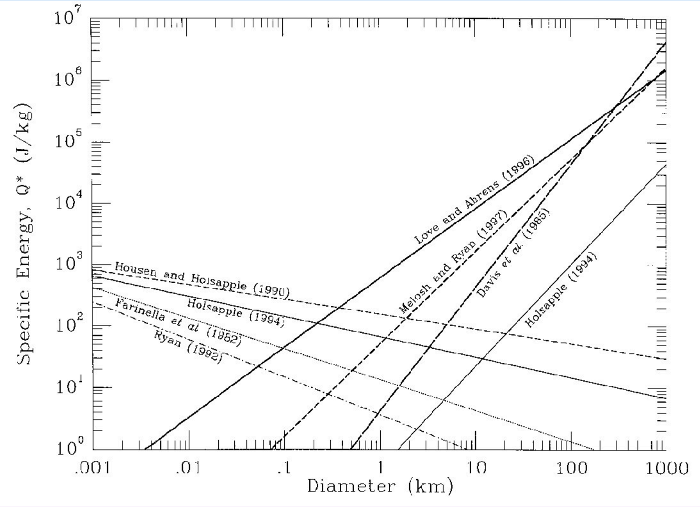
• Asteroids D>150m have a maximum spin rate of 11/day

• This is interpreted as evidence for their rubble pile structure, because for a strengthless material faster spins produce centrifugal tensile forces at the equator that are greater than the compressive gravity forces

• Such structure is also expected from collisional evolution models, since the energy required to break-up a planetesimal is much lower than that required to disperse the fragments

• Smaller asteroids are fast rotators, implying monolithic rocks (although very little strength actually required)

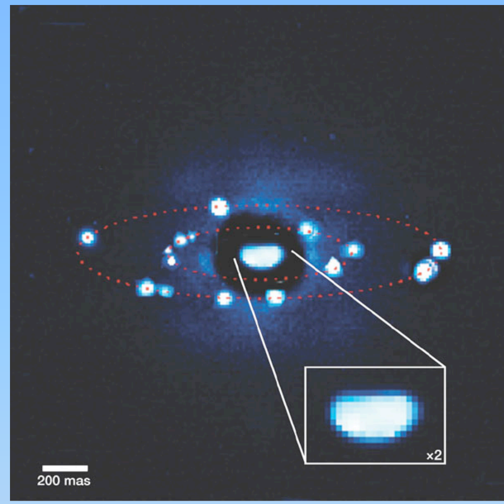




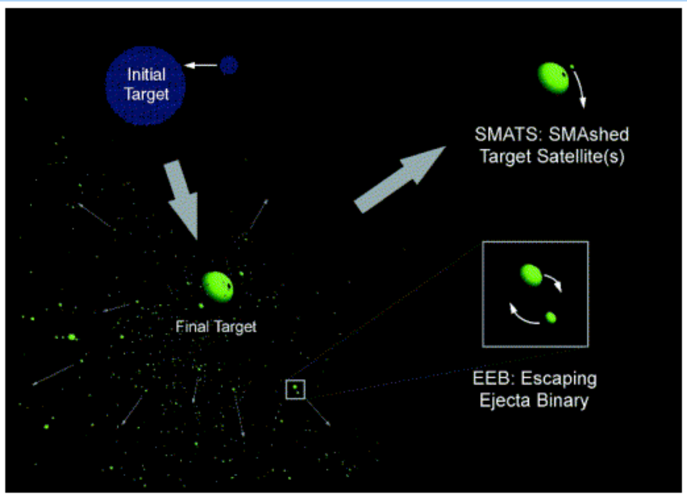
Asteroids - binarity

~15% of asteroids are binary

Most have size ratios of 10-25 and orbital separations at ~10R_p, but more now seen at 3-4 size ratio and to 23-100R_p



Binaries form naturally in collisions either orbiting the primary, or in escaping ejecta (Michel et al. 2001; Durda et al. 2004), but also form in tidal encounters with planets (Walsh & Richardson 2005)



- First triple asteroid system discovered around 87 Sylvia (Marchis et al. 2005): primary is 280km rubble pile, while moonlets orbit on prograde circular equatorial orbits at 710 and 1360km

Asteroids - Trojans

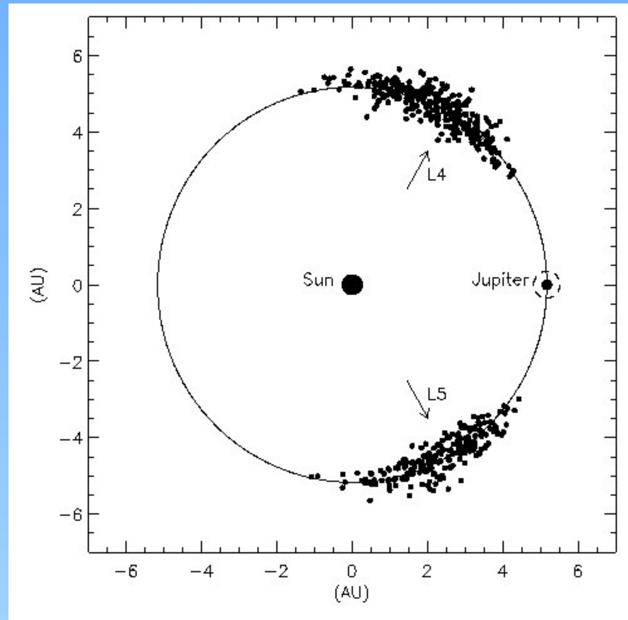
- Orbiting Jupiter's L4 and L5 points, with more around L4 (though not sure if this is observational bias)

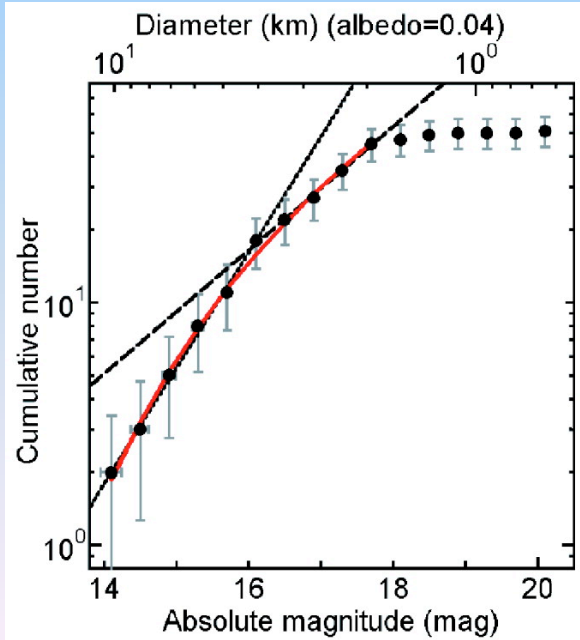
- Size distribution $n(D)\ D^{2.39}$ for D>5km
  and $n(D)\ D^{1.28}$ for D<5km
  (Yoshida & Nakamura 2005)

- There is just one known Trojan binary (617 Patroclus)

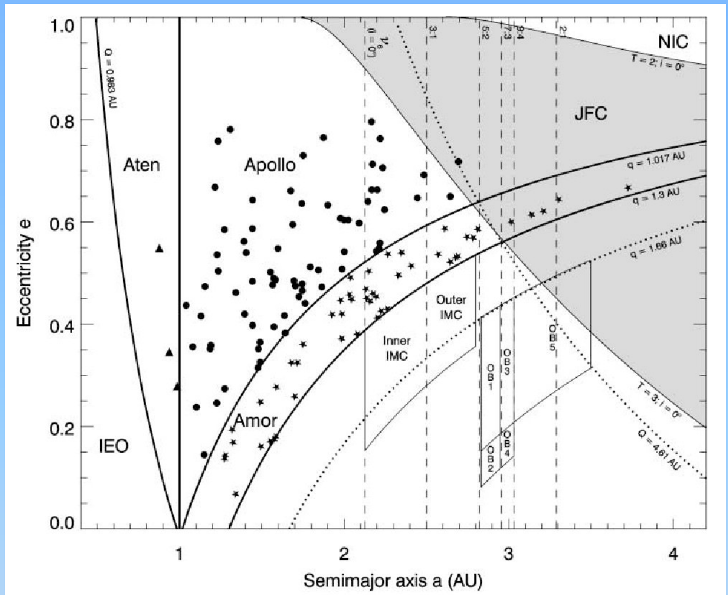
- Origin is thought to be formation near Jupiter then capture while Jupiter was growing, possibly with help of gas drag/collisions, though some seem to be passing

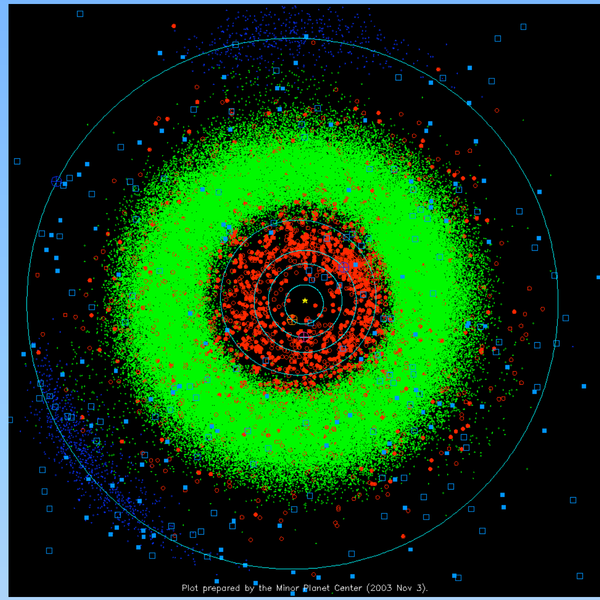
- Other planets also have Trojans (e.g., 4 at Mars)





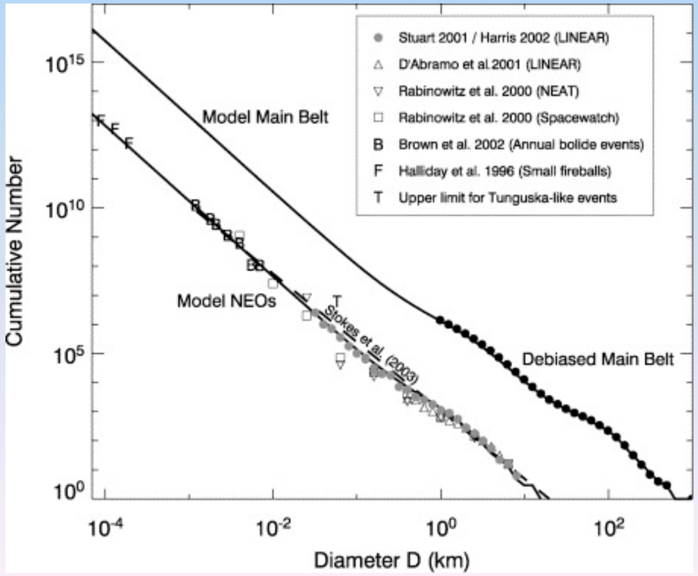
Asteroids – Near Earth Asteroids





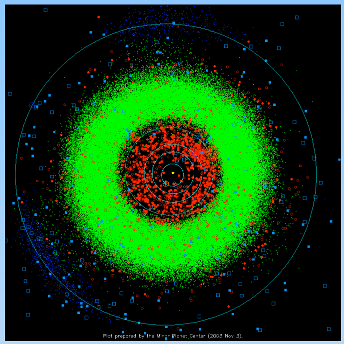
Near Earth Asteroids are those that come within 1.3AU of Earth: Amors (cross Mars), Apollos (cross Earth a>1), Atens (cross Earth a<1)

Origin is in the Asteroid belt: migration to chaotic region where eccentricities pumped up (consistent with cosmic ray exposure ages, size distribution, orbital distribution, impact rate on terrestrial planets, Bottke et al. 2002)



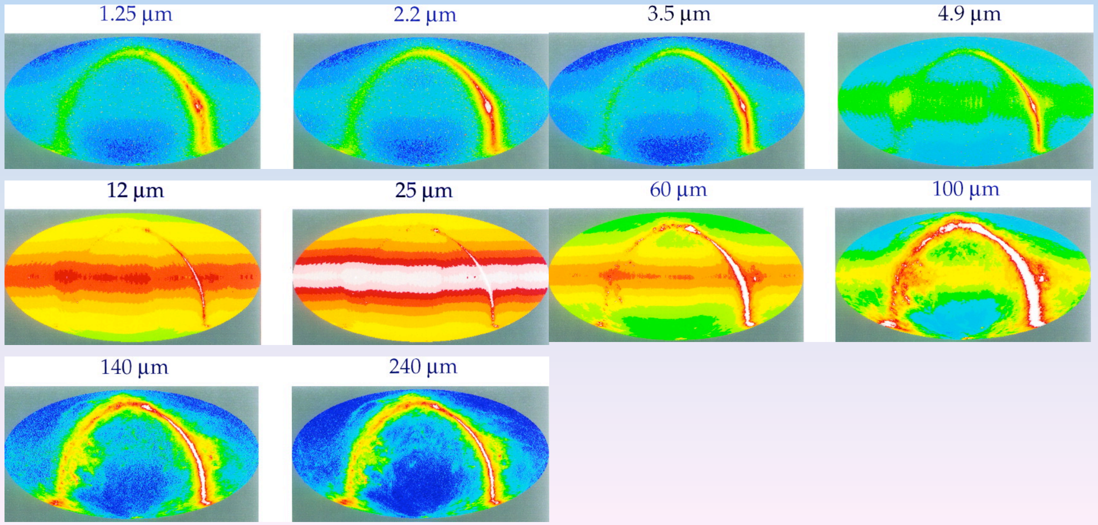
Dust: Zodiacal cloud

Dust created in collisions between asteroids in the Asteroid Belt spirals in toward the Sun meaning the Earth is enveloped in a dust cloud



This dust cloud is observable to the naked eye just before (after) sunrise (sunset) as the zodiacal light (sunlight scattered by dust)

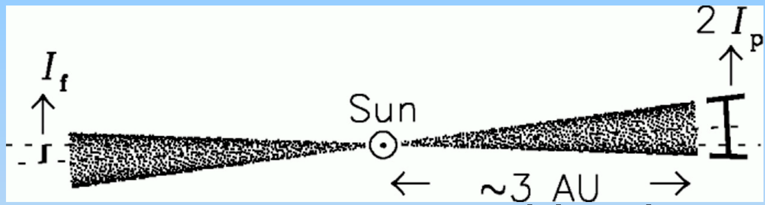
It is also the brightest thing in the infrared sky outside the Earth's atmosphere (e.g., Kelsall et al. 1998): the dust is heated by the Sun and reemits radiation in the IR



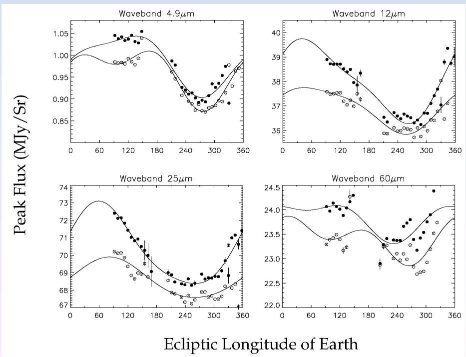
Zodiacal Cloud: structures

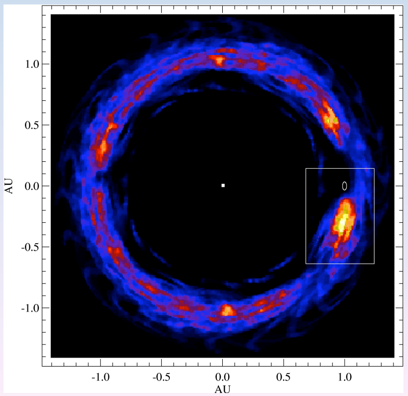
IRAS and COBE showed that the zodiacal cloud is not smooth and featureless:

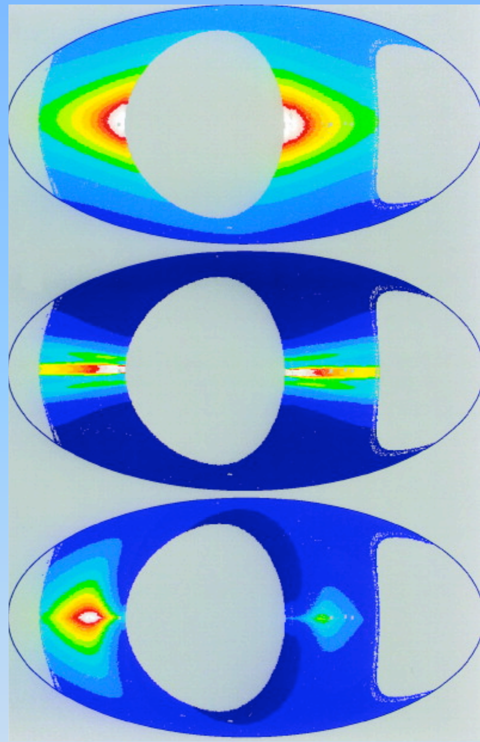
Dust bands come from break-up of asteroid families = dust with common proper inclinations (Vokrouhlicky et al 2008)



Earth's resonant ring: caused by dust trapped in resonance with the Earth (Dermott et al. 1994); none detected at Mars or at Jupiter's Trojans (Kuchner et al. 2000)

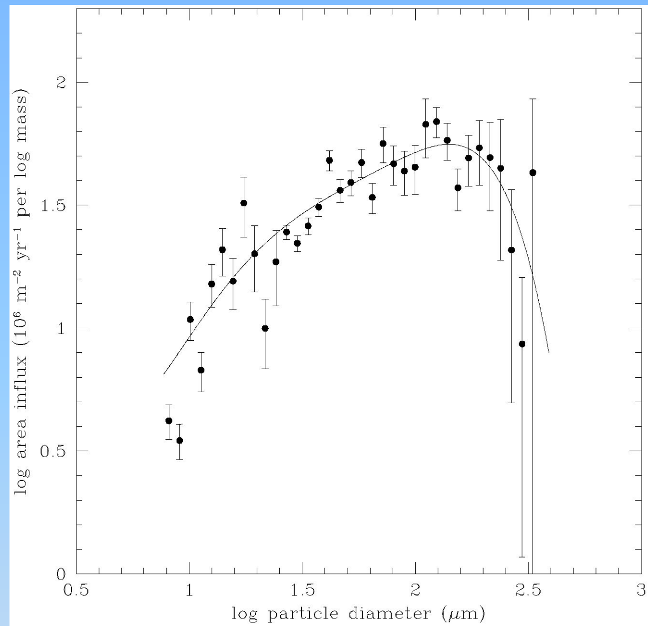




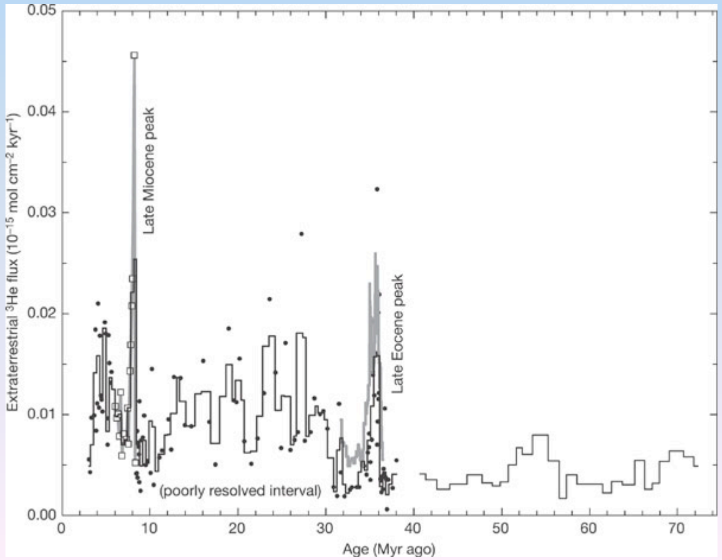


Smooth background gives inclination distribution and so relative contribution of asteroids and comets (still debated, Losue et al. 2007); also offset in centre of symmetry from Sun and the ZC is warped

Zodiacal Cloud: accretion by Earth



LDEF (long duration exposure facility) showed the size distribution of material accreted by the Earth peaks at a few 100μm, fairly representative of dust in ZC in general (Love & Brownlee 1993)



Dust accreted by Earth is also evident in deep-sea sediments in the ^{3}He record which is extraterrestrial in origin – recent discovery of peaks in the late Miocene and late Eocene (Farley et al. 2006)

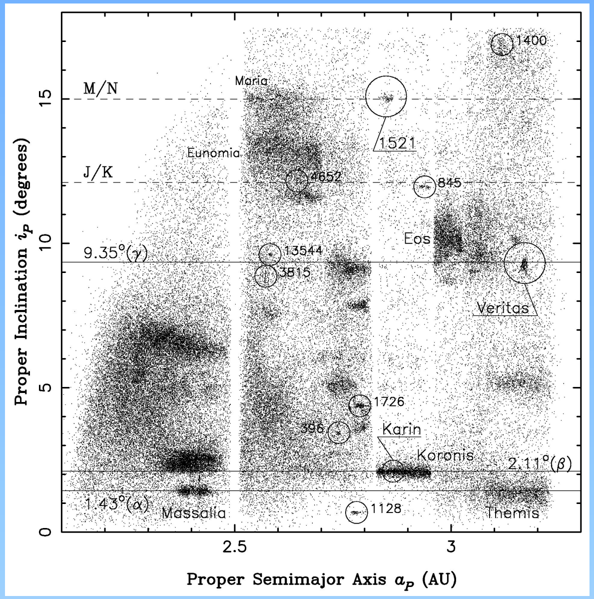
Largest "dust" accreted is seen as meteors which are heated in Earth's atmosphere (mm-sized grains), but these come from comets which is why there are showers when Earth goes through comet tail

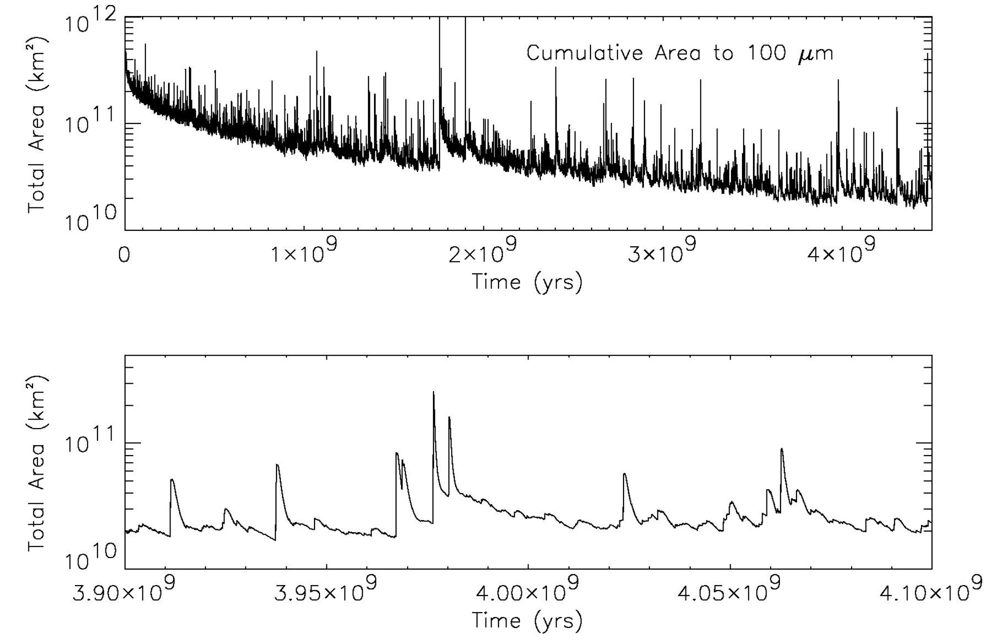
Zodiacal Cloud: evolution

Dust bands now linked dynamically to the small families created recently (last few Myr) – Nesvorny et al. 2002

The same events also linked to the accretion of dust onto the Earth (Farley et al. 2006)

The evolution of the zodiacal cloud is thought to be stochastic, punctuated by large increases in dust content when large asteroids collide





Kuiper Belt

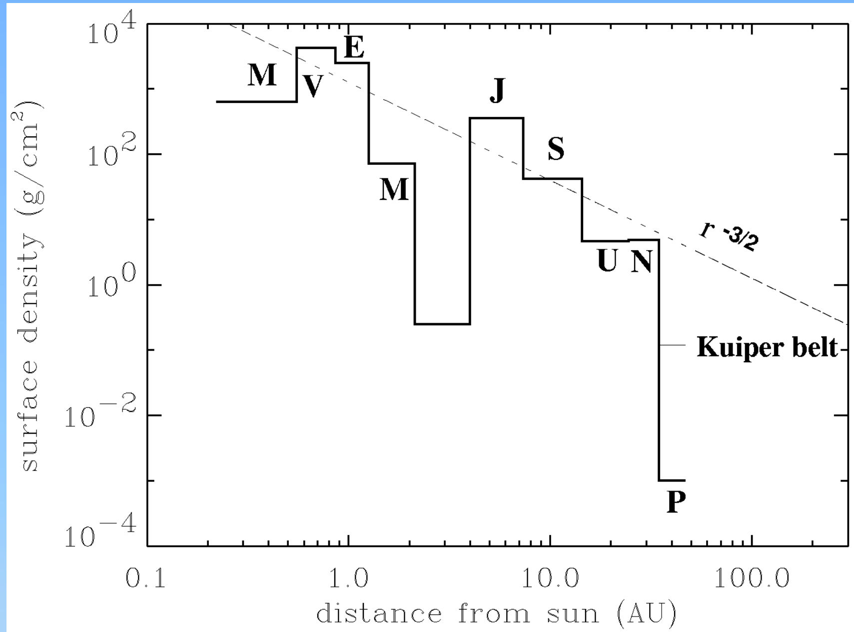
• Belt of icy comets orbiting the Sun beyond 30 AU

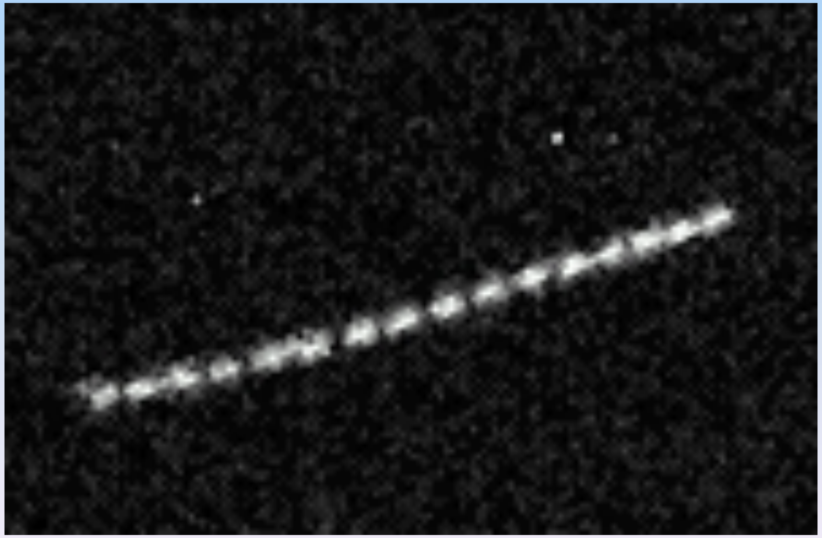
• Hypothesised in 1951 by Kuiper to explain origin of comets; also explains missing mass of the solar system

• Leonard (1930) and Edgeworth (1943, 1949) may also claim to have predicted this belt

• First KBO, 1992 QB_1, discovered by Jewitt & Luu (1993)

• KBOs are discovered by looking for objects moving at the right speed across the sky; e.g., Quaoar (right)



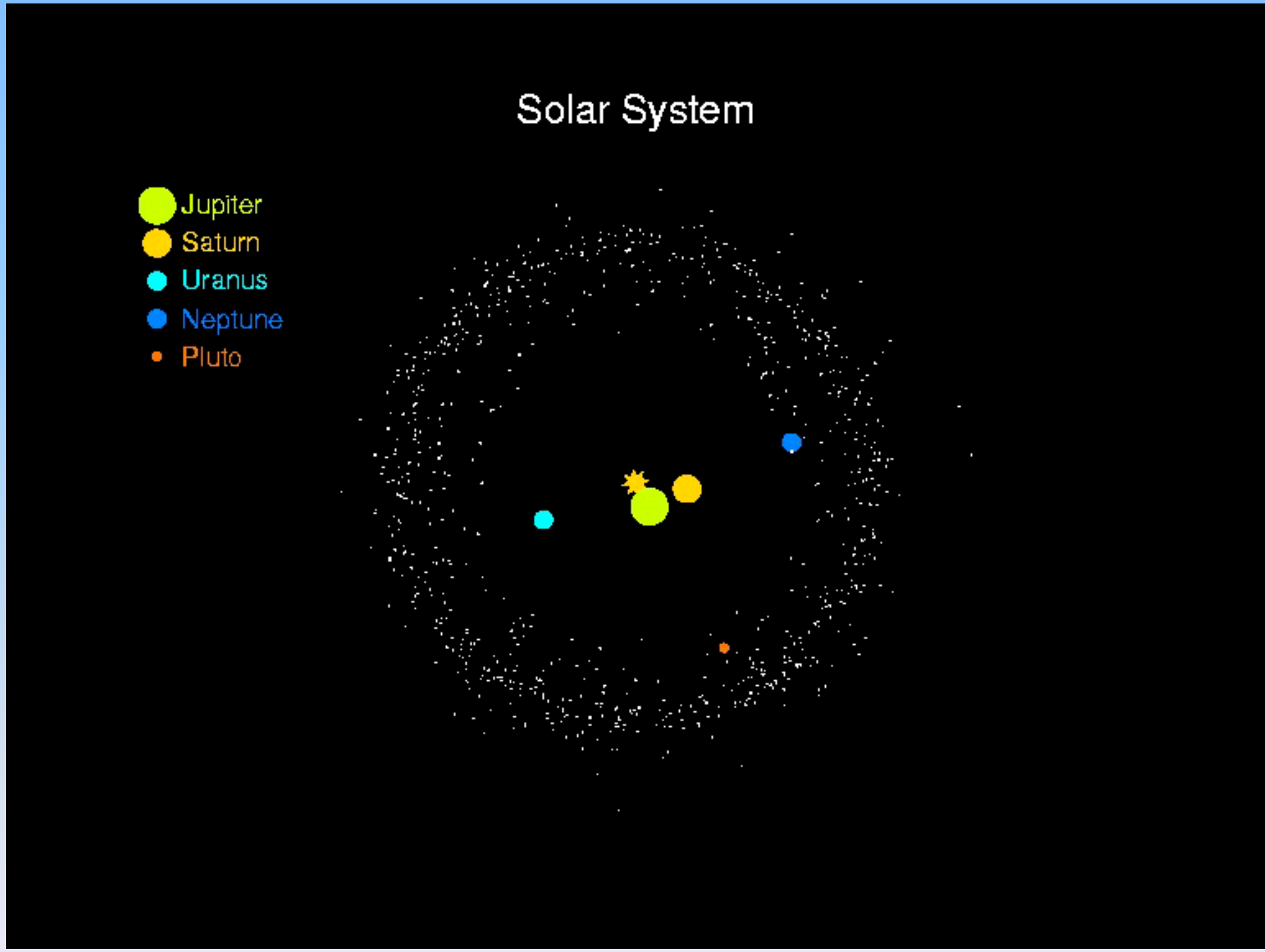


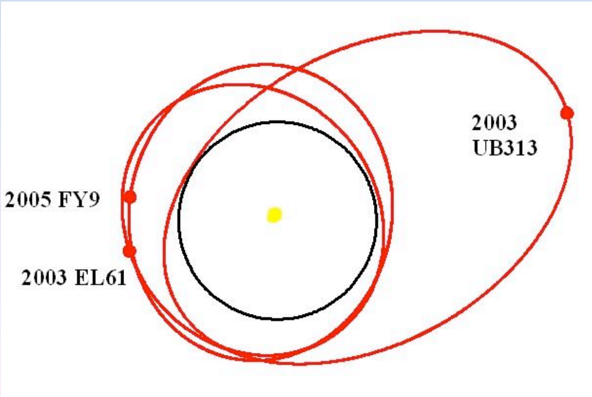
Kuiper Belt

The Outer Solar System

- Now almost 1000 KBOs have been discovered

- Argument over whether Pluto is a planet or a large KBO sparked by discovery of 2003 UB313 (now Eris) which at ~2860km is larger than Pluto (Brown, Trujillo & Rabinowitz 2005)



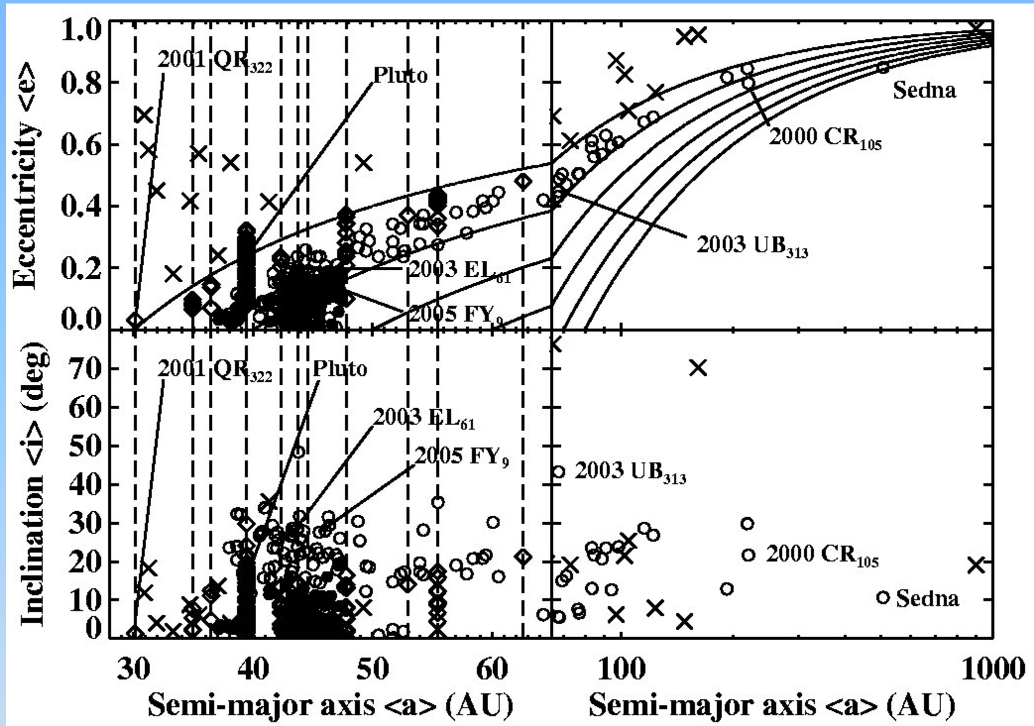


Kuiper Belt – dynamical populations

The orbital distribution of KBOs shows three distinct populations:

• Resonant KBOs: trapped in Neptune's 3:2, 2:1, 5:3, 5:2, 9:5, 7:3 resonances (e.g., Pluto); also one Neptune Trojan 2001QR$_{322}$

• Classical KBOs: 37-47 AU, low e and I, but split into hot (I>5^0) and cold (I<5^0) populations with different physical characteristics; possible family (Chiang 2002; Raggozine & Brown 2007) and gaps due to secular resonances; outer edge is not observational bias (Trujillo & Brown 2001)



• Scattered KBOs: with high eccentricity and perihelia close to Neptune

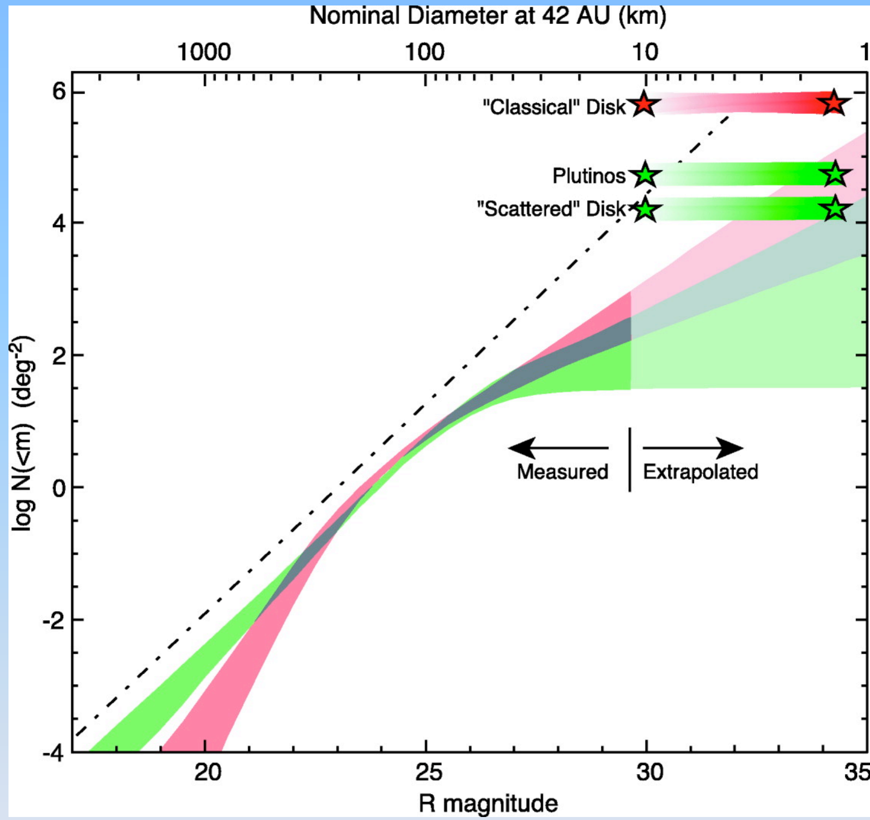
• Also Sedna-like objects with perihelia beyond Neptune (q_{sedna}=76AU, $q_{2000CR105}$=44AU); origin in cluster (Brasser et al. 2006) or planet X?

Kuiper Belt – size distribution

- Size distribution turns over at ~100km for all populations, and different populations have different size distributions (Bernstein et al. 2004); the break at 40km is predicted by collisional evolution models (Pan & Sari 2005)

- Hsiang-Kuang et al. (2006) claimed occultations of 100m KBOs in Xray obs of Sco X1, but found to be instrumental

- Total mass is 0.05-0.3M_{earth} (Luu & Jewitt 2002; Chiang et al. 2006)



Missing mass problem: 100 times that is required to form Pluto within 100Myr (Kenyon & Luu 1998; 1999); also expected from extrapolation of surface density distribution of solids in the solar system (Weidenschilling et al. 1977)

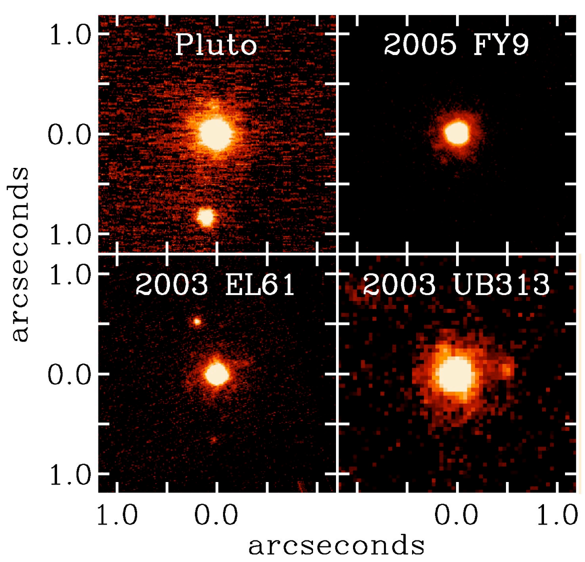
Kuiper Belt - binarity

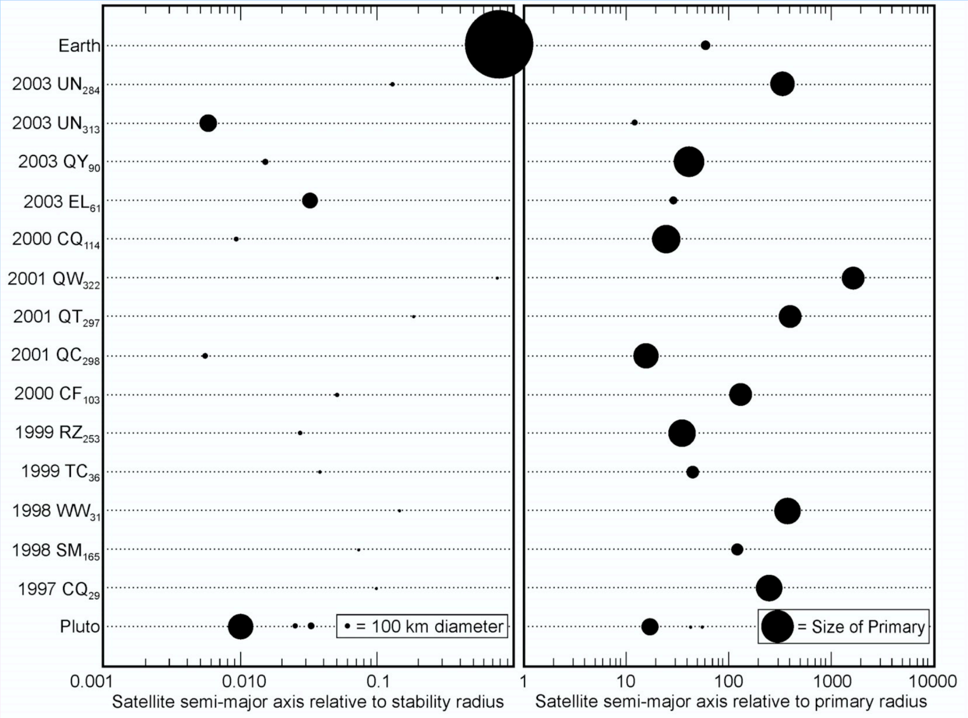
15 KBO binaries now known: ~11% of all KBOs have companions (Stephens & Noll 2006; Brown et al. 2006) with population differences - cold classical belt (22%), hot classical belt (5.5%), scattered disk (11.5%)

Different to asteroid binaries: high mass ratio (0.1-1 cf 10^{-3}-10^{-4}) and large orbits (20-2000R_p cf 3-10R_p)

Formation: collisions (Canup 2005; Stern 2006), capture (Goldreich et al. 2002), 3-body exchange reactions (Funato et al. 2006)

Most models require the KB to be much more massive (for high collision frequency) -> binarity is primordial, but Petit & Mousis (2004) show binarity must have been 10x greater



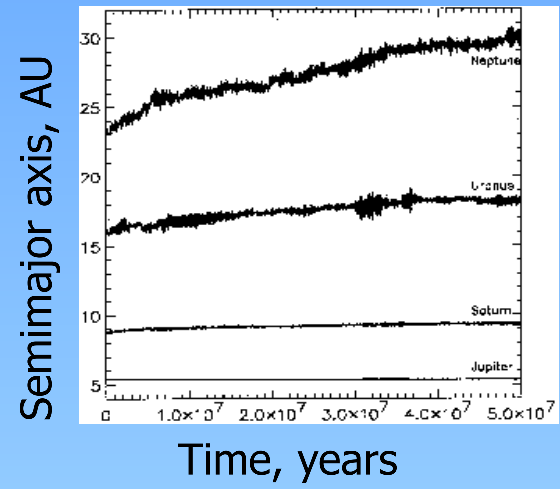


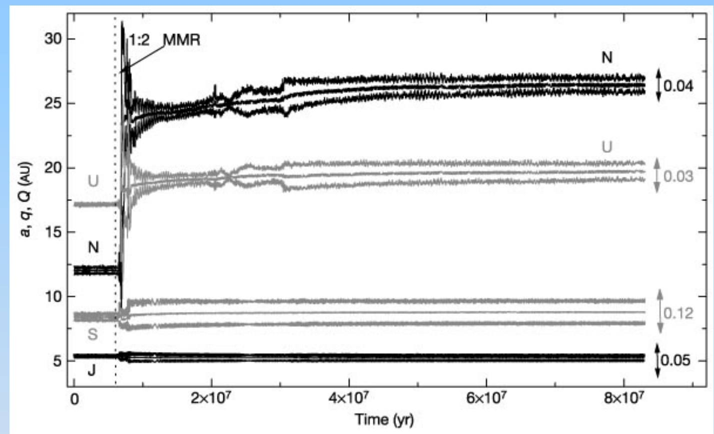
Kuiper Belt - evolution

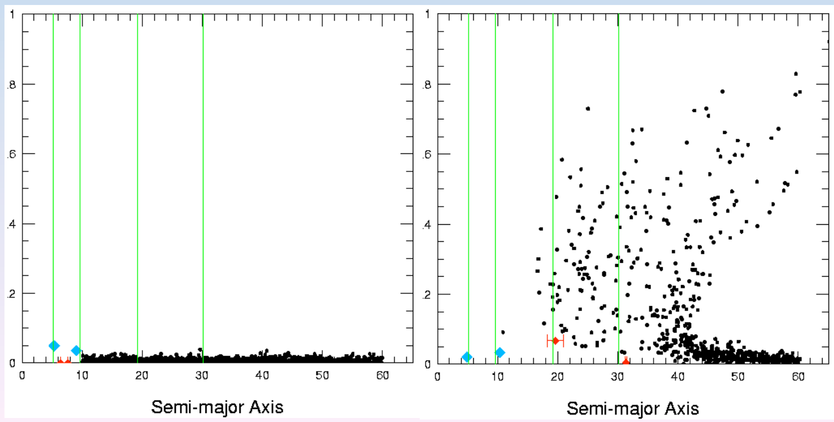
There is still much debate as to origin of structure in the KB, though outward migration of Neptune is origin of resonant populations (Malhotra 1993)

Such migration probably came from scattering of primordial planetesimals the initial configuration of outer planets is debated:

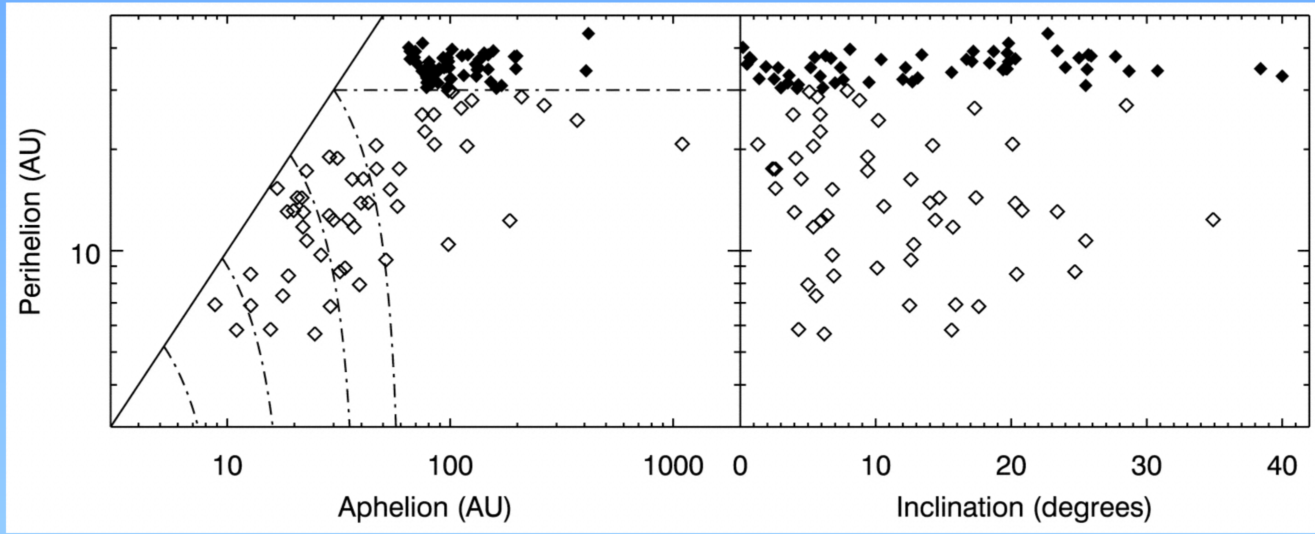
- Hahn & Malhotra (1999) place them slightly interior to current locations
- Morbidelli, Tsiganis, Levison, Gomes (2005) put orbits much closer and propose slow migration until JS crossed 2:1 resonance
- Thommes et al. (2002) place UN between JS







Centaurs

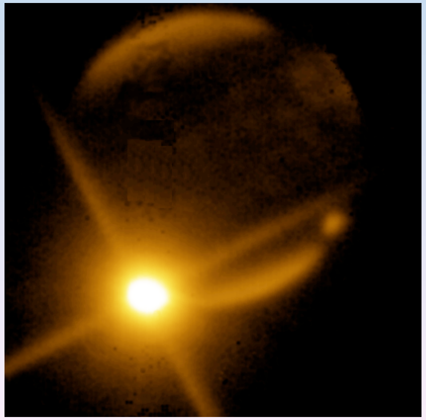


Centaurs are the population of planetesimals orbiting between Jupiter and Neptune

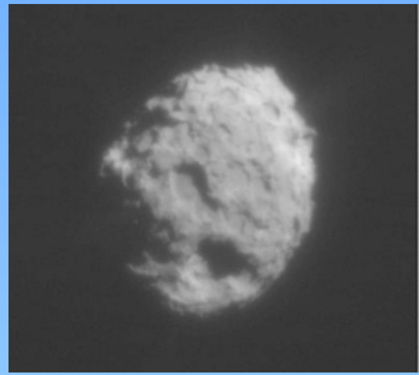
Long term dynamical simulations show this region to be chaotic with orbits lasting just 10-100Myr (Levison & Duncan 1997)

Centaurs are thought to originate in the Kuiper belt

Their ultimate fate for most is ejection, but some end up as Jupiter family comets, and a few % end up colliding with a giant planet (Tiscareno & Malhotra 2003)

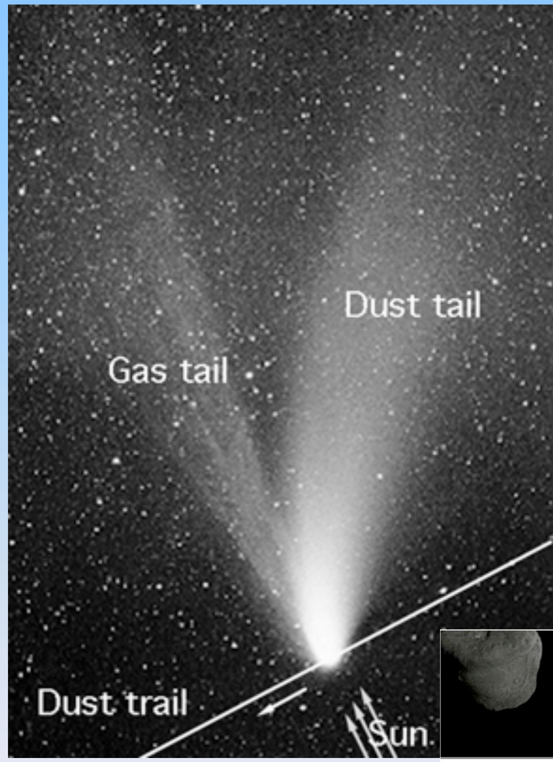


Comets



- Comets have a nucleus a few km across = icy chunks, frozen gases, dust

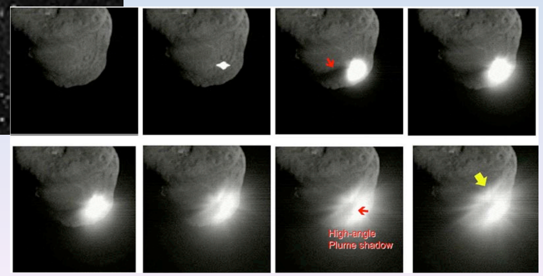
- As they approach the Sun they are heated and gas and dust is released (Reach et al. 2007)



- This forms a coma ~100,000 km across

- The solar wind pushes this into a bright tail pointing away from the Sun (we see gas in fluorescence, light scattered by dust)

- Stardust flew past comet Wild 2 in Jan 2004 taking pictures of its nucleus, Deep Impact collision with 9P/Tempel 1 in 2005



Comets

• Comets have highly eccentric orbits

• We see them when close to perihelion, but they spend most of their orbits far from Sun

• There are two types of comet:

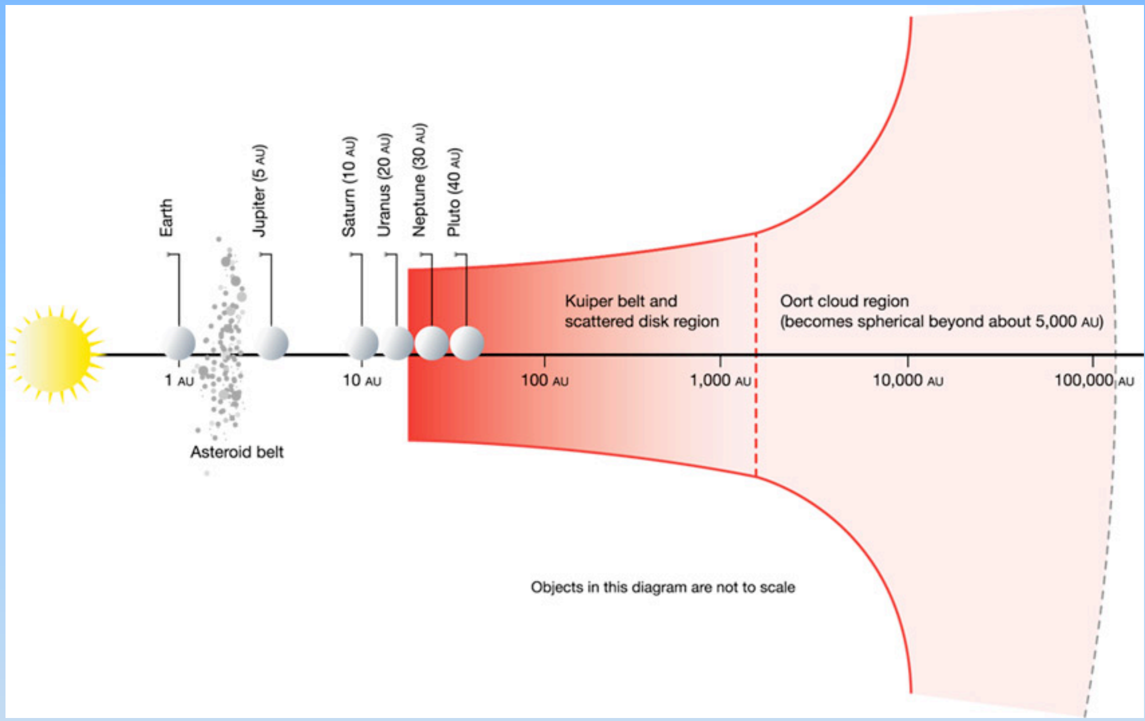
- Short period comets
  Have an orbital period < 200 years
  Thought to come from the Kuiper Belt
  e.g., Halley

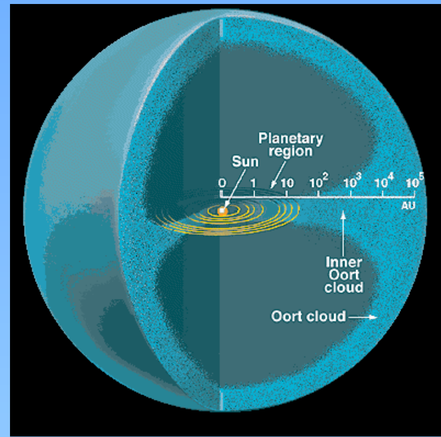
- Long period comets
  Have an orbital period of several Myr
  Thought to come from Oort cloud

Comet McNaught

Comet 17P/Holmes
(e.g., Montalto et al. 2008)

Oort Cloud





The Oort cloud extends to 100,000 AU and beyond
5000 AU is roughly spherical in shape (Oort 1950)

Total mass is 1-50M_{earth} locked into 0.1-5x10^{12} comets

Natural outcome of planetary system formation

Material is more pristine than that of JFCs since little processing has occurred since formation

Comets fed into inner SS by galactic tides (not encounters) (Dybczynski 2006)