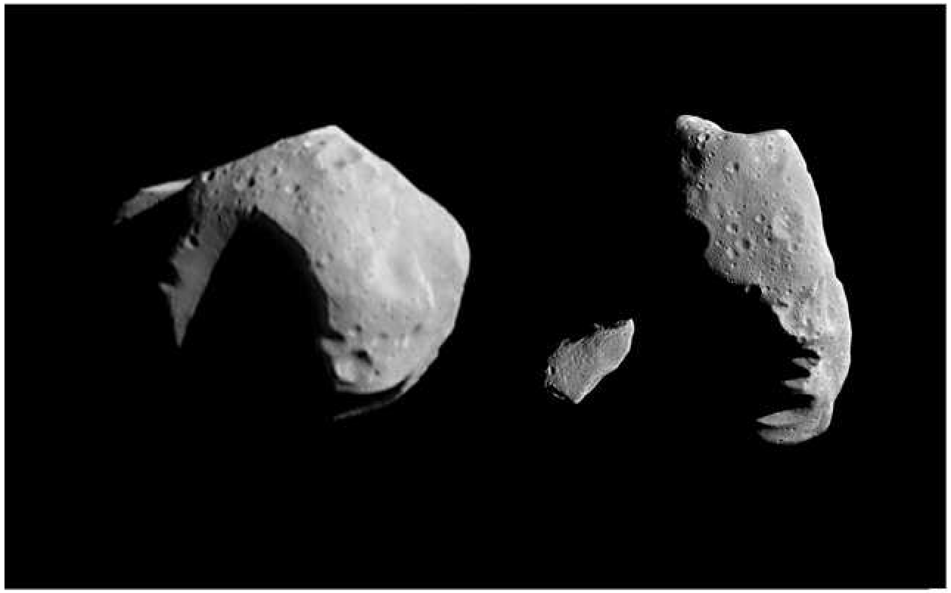
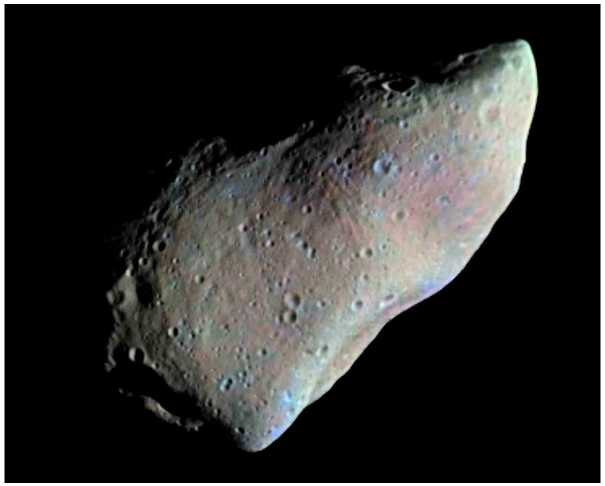
Small Solar System Bodies: Asteroids, Comets, and Transneptunians

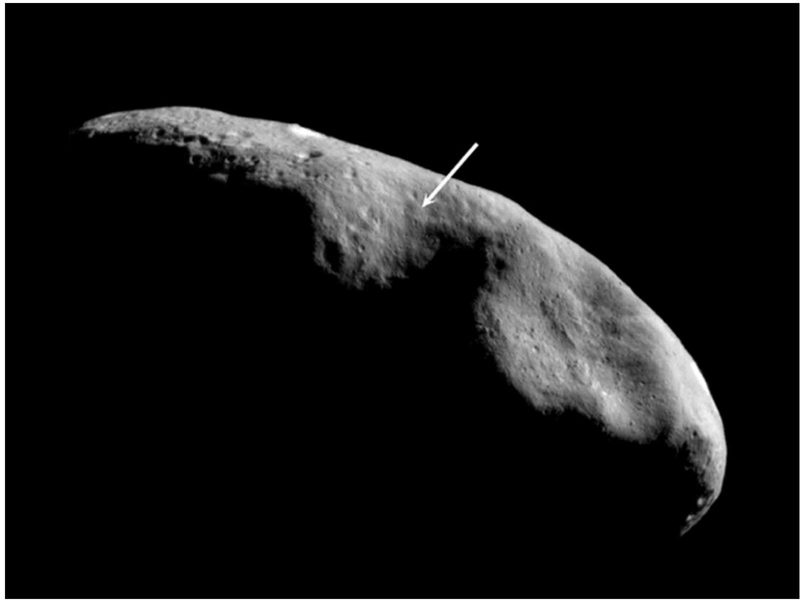


Several asteroids surveyed by interplanetary probes (Mathilde, Eros by NEAR Shoemaker; Gaspra [$19 \times 12 \times 11$ km], Ida [58×23 km] by Galileo)



951 Gaspra (NASA)

Asteroids: Minor planets mostly between Mars and Jupiter (main belt), diameters <1000 km

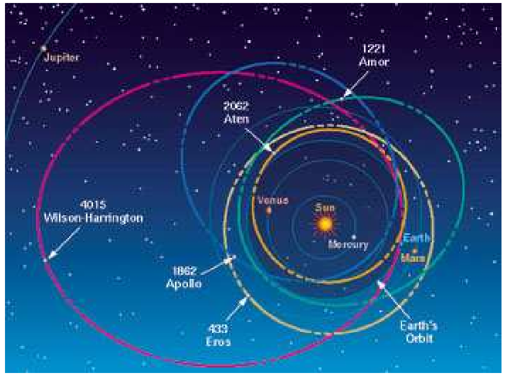


2001 Feb 12: NEAR lands on Eros

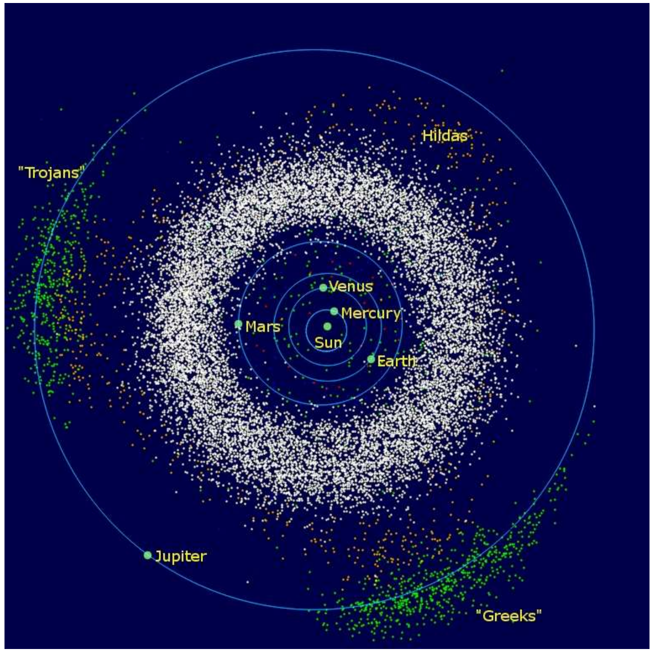
First discovery in 1801 (Piazzi: Ceres, diam. 1000 km)
Today >100000 known, only 7 with diameters >300 km
Total mass $\sim$0.5% of Earth (40% of moon), of which $\sim$30% in Ceres, 75% are C-type (carbonaceous), 17% S-type (silicaceous), and 8% M-type (metallic) asteroids.

MOVIE TIME:

- http://near.jhuapl.edu/iod/20010205/index.html: Rotation of Eros [2000 Dec 3/4]
- http://near.jhuapl.edu/iod/20010731/index.html: descent onto Eros

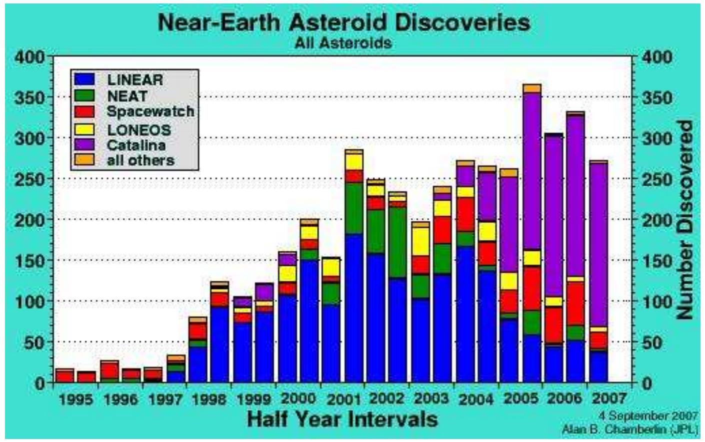


NEAs: Near Earth Asteroids:
Earth path crossing (Atens, Apollos),
Earth approaching (Amors).



Wikipedia

Orbit dynamics leads to structuring of the asteroid belt: asteroid families.



PHA: Potential hazardous Asteroids: >150m, <0.05 AU: ~1000 known, see http://neo.jpl.nasa.gov/index.html

Estimate: there are >1000000 Earth orbit crossing asteroids

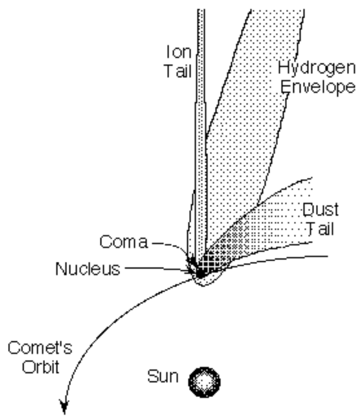
Comets

153P/Ikeya-Zhang (©M. Jäger)

Comet Hale Bopp over Bamberg, 1997 spring

Comet Hale Bopp, March 30, 1997

Structure, IV



NASA

Major components of a comet:

- Nucleus: "Dusty Snowball" (Whipple, 1951), 1–50 km
  dominated by water ice, plus up to 15–20% CO_2 and CO
- Coma: 10^4–10^5 km, evaporated gas surrounding nucleus
  includes H_2O, CO_2, CO, but also H_2S, CH_3OH, H_2CO, NH_3, HCN, CH_4, S_2
- Ion tail: Ionized gas, typical extent up to 10^8 km, often bluish
- Dust tail: Dust evaporated away from nucleus, typical size $\sim 10^6$–10^7 km.

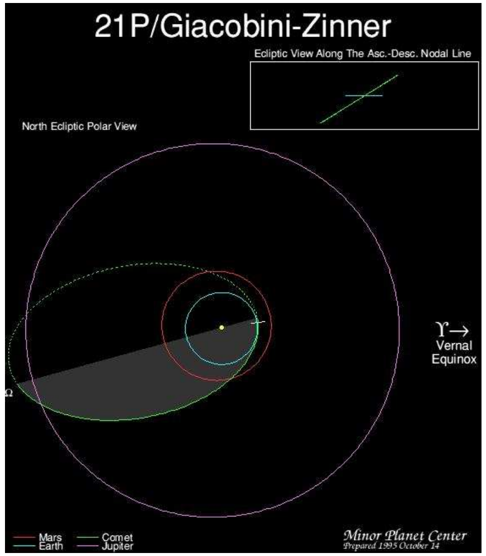
High volatility species indicate origin in cool regions of solar system and "storage" out there until recently.

Structure, V

Bust of Apian (Ruhmeshalle, Munich)

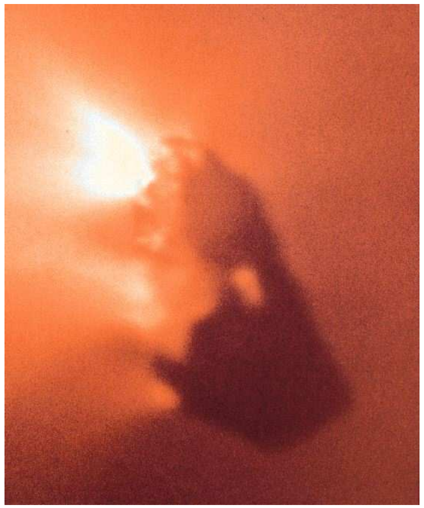
How do cometary tails form?

- tails always point away from the sun (Apianus, 1531) $\Longrightarrow$ sun causes the phenomenon
- Dust tail: scattered sun light.
- Dust particles are accelerated by radiation pressure
- Gas tail: ionised plasma, ions emit light by fluorescence
- Wurm (1943) plasma can not be acccelerated by radiation pressure
- Biermann (1951): There must be a solar wind of particles



siderial period: 6yr 227d, perihel: 1.037 AU, aphel: 6.015 AU
rediscoverd by Zinner, Assistent at Bamberg observatory (later its second director)
first comet oberved by a space probe: 1985: ICE (International Comet Explorer)
flys through tail in 7800 km distance from core

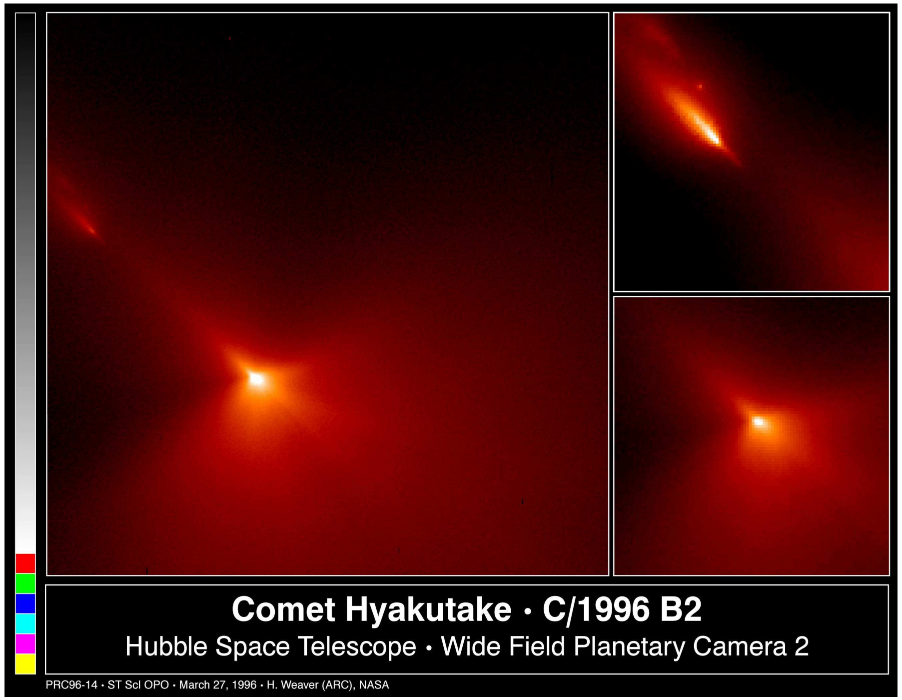
Halley

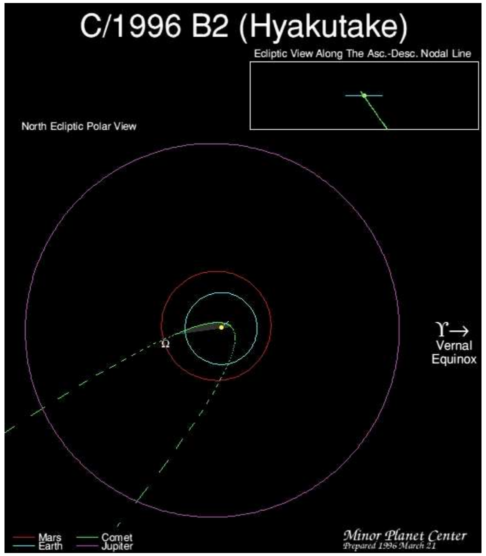


ESA

1P/Halley:

- Orbital period: 76–79.3 year orbit (earliest recorded appearence: 239 B.C, famous: 1066, Tapestry of Bayeux).
- Analyzed in detail during 1986 return, flyby of ESA's Giotto spacecraft close to nucleus, further analysis by Russian Vega 1 and 2 probes, Japanese Suisei and Sakigake, and NASA's International Cometary Explorer.
- "International Halley Watch" with strong contributions from Bamberg observatory.





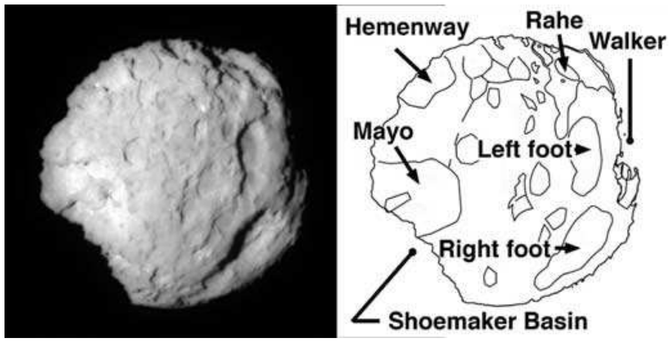
Original Semi-major axis: ∼400 AU, closest approach to Earth: 0.1 AU

$i = 125°$; $e > 0.999784$

Pre-perihelion Orbital period: ∼8000 years

Post-perihelion Orbital period: ∼14000 years

Comet Wild 2, I



NASA, stardust mission, size ∼5 km

NASA's Stardust mission: flyby at comet Wild 2 on 2004 January 2, collection of particles from vicinity of comet's nucleus (closest approach: 240 km), impacted with samples in Utah on 2006 January 15

P/Wild 2: large semi-major axis, perihelion outside Mars after Jupiter encounter in 1974 (∼ Jupiter before that) ⟹ Material has not been processed by Sun before sample return.

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COMET SHOEMAKER-LEVY (1993e)

Cometary images have been discovered by C. S. Shoemaker, E. M. Shoemaker and D. H. Levy on films obtained with the 0.46-m Schmidt telescope at Palomar. The appearance was most unusual in that the comet appeared as a dense, linear bar ∼ 1′ long and oriented roughly east-west; no central condensation was observable, but a fainter, wispy 'tail' extended north of the bar and to the west. The object was confirmed two nights later in Spacewatch CCD scans by J. V. Scotti, who described the nuclear region as a long, narrow train ∼ 47″ in length and ∼ 11″ in width, aligned along p.a. 80°-260°. At least five discernible condensations were visible within the train, the brightest being ∼ 14″ from the southwestern end. Dust trails extended 4′.20 in p.a. 74° and 6′.89 in p.a. 260°, roughly aligned with the ends of the train and measured from the midpoint of the train. Tails extended > 1′ from the nuclear train, the brightest component extending from the brightest condensation to 1′.34 in p.a. 286°. The measurements below refer to the midpoint of the bar or train.

1993 UT	α_{2000}	δ_{2000}	m_1	*Observer*
Mar. 24.35503	12ʰ26ᵐ39ˢ.27	−4°03′32″.9	14	Shoemaker
24.43072	12 26 37.21	−4 03 23.0		"
26.29531	12 25 42.24	−3 57 55.7	13.9	Scotti
26.30479	12 25 42.09	−3 57 53.7	16.7	"
26.31448	12 25 41.63	−3 57 53.7		"
26.41291	12 25 38.70	−3 57 34.8		"

C. S. Shoemaker, E. M. Shoemaker, D. H. Levy and P. Bendjoya (Palomar). Measurers D. H. Levy, J. Mueller, P. Bendjoya and E. M. Shoemaker.
J. V. Scotti (Kitt Peak). Last observation made through cirrus.

The comet is located ∼ 4° from Jupiter, and the motion suggests that it may be near Jupiter's distance.

SUPERNOVA 1993E IN KUG 0940+495

D. D. Balam and G. C. L. Aikman report a measurement of V = 20.3 ± 0.1 and $B - V$ = +0.51 on Feb. 26.28 UT, using the 1.85-m reflector (+ CCD) at the Dominion Astrophysical Observatory.

1993 March 26 *Brian G. Marsden*

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COMET SHOEMAKER-LEVY (1993e)

Further precise positions have been reported as follows:

1993 UT	α_{2000}	δ_{2000}	m_1	*Observer*
Mar. 27.12479	12ʰ25ᵐ17ˢ.77	−3°55′32″.3		McCrosky
27.14850	12 25 16.94	−3 55 24.6		"
27.30417	12 25 12.37	−3 54 57.6	15	Tatum

R. E. McCrosky and C.-Y. Shao (Oak Ridge). 1.5-m reflector + CCD. 'Meteoric' appearance! 'Train' 41″ long in p.a. 78°-258°.
J. B. Tatum and D. D. Balam (Victoria). 0.25-m Schmidt.

The following parabolic orbital elements satisfy the nine observations and indicate minimum approach to Jupiter 0.31 AU on 1993 Mar. 30:

T = 1994 Aug. 3.441 TT ω = 300°.459, Ω = 344.563, i = 2.322 (2000.0)
q = 2.36996 AU

The following representative elliptical orbital elements give the minimum approach to Jupiter as 0.04 AU on 1992 July 28:

T = 1988 Dec. 5.767 TT ω = 43°.253
e = 0.18714 Ω = 347.657 (2000.0)
q = 3.91756 AU i = 2.684

This ellipse puts the comet at r = 5.4 AU around Jupiter encounter with Jupiter-free values of q = 5.8 and 5.2 AU in 1979 and 1998, respectively. The ends of the Mar. 27 Oak Ridge train can be satisfied by varying the place in orbit by ±0.007 day at Jupiter encounter. Considering only its distance, the comet would have been as bright at its Feb. 1992 opposition as it is now, but splitting presumably occurred near Jupiter (as with P/Brooks 2 in 1886), and this is presumably to be associated with brightening.

1993 TT	α_{2000}	δ_{2000}	Δ	r	ϵ	β	m_1
Feb. 22	12ʰ39ᵐ.75	−5°16′.9	4.776	5.591	142°.3	6°.2	13.9
Mar. 4	12 36.04	−4 57.1	4.694	5.598	153.3	4.6	13.8
14	12 31.65	−4 32.5	4.640	5.604	164.4	2.7	13.8
24	12 26.84	−4 04.6	4.616	5.611	175.6	0.8	13.8
Apr. 3	12 21.93	−3 35.3	4.623	5.617	173.0	1.2	13.8
13	12 17.26	−3 06.9	4.660	5.623	162.0	3.2	13.8
23	12 13.11	−2 41.2	4.727	5.628	151.1	5.0	13.9

1993 March 27 *Brian G. Marsden*

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1993 FW

J. Luu, University of California at Berkeley; and D. Jewitt, University of Hawaii, report the discovery of a second very faint object with very slow (3″/hr) retrograde opposition motion. The object was detected in CCD images obtained with the University of Hawaii's 2.2-m telescope at Mauna Kea. The object appears stellar in 0″.8 seeing, with an apparent Mould magnitude $R = 22.8 \pm 0.1$ measured in a 1″.6-radius aperture. The color $V - R = +0.4 \pm 0.1$.

1993 UT	α_{2000}	δ_{2000}
Mar. 28.41684	12ʰ27ᵐ06ˢ.31	−3°00′12″.7
28.59830	12 27 05.52	−3 00 07.0
29.41934	12 27 01.90	−2 59 42.2
29.42846	12 27 01.85	−2 59 41.8

Computations by B. G. Marsden indicate that 1993 FW is currently between 38 and 56 AU from the earth. Similarity in motion and brightness to 1992 QB_1 suggests that 1993 FW is another Kuiper Belt candidate, and the orbit selected below is again the direct circle. The object's phase angle reached a minimum of 0°.002 on Mar. 28.0 UT.

Epoch = 1993 Mar. 14.0 TT u = 359°.468
Ω = 187.896 } 2000.0
a = 42.451 AU i = 8.029

1993 TT	α_{2000}	δ_{2000}	Δ	r	ϵ	β	V
Mar. 24	12ʰ27ᵐ.43	− 3°02′.4	41.456	42.451	176°.0	0°.1	23.2
Apr. 3	12 26.70	− 2 57.4	41.457	42.451	174.0	0.1	23.2
13	12 25.98	− 2 52.4	41.487	42.451	163.9	0.4	23.2
23	12 25.30	− 2 47.7	41.545	42.451	154.0	0.6	23.2
May 3	12 24.70	− 2 43.5	41.631	42.451	144.1	0.8	23.3

COMET SHOEMAKER-LEVY (1993e)

Luu and Jewitt also report that their CCD imaging of this comet with the 2.2-m telescope at Mauna Kea on Mar. 27 showed as many as 17 separate sub-nuclei "strung out like pearls on a string" over a range of 50″ along p.a. 77°-257°. The brightest sub-nuclei were four or five in from the southwestern end. The appearance was unchanged on Mar. 28.

1993 March 29   *Brian G. Marsden*

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COMET SHOEMAKER-LEVY (1993e)

Further selected precise positions:

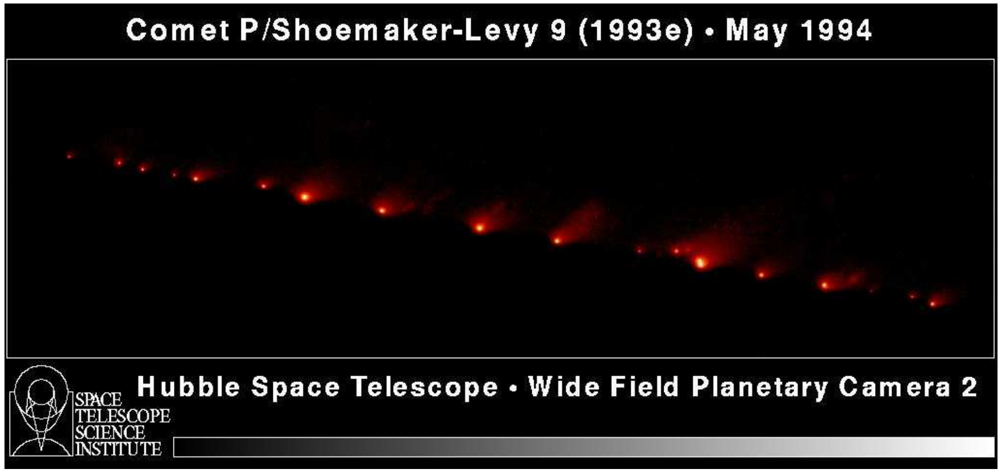
1993 UT	α_{2000}	δ_{2000}	m_1	*Observer*
Mar. 15.57153	12ʰ30ᵐ52ˢ.17	−4°28′12″.3	16.0	Endate
15.58611	12 30 51.73	−4 28 09.7		"
26.23333	12 25 43.71	−3 58 04.9	15	Naranjo
28.24097	12 24 44.97	−3 52 16.3		"
28.25677	12 24 44.36	−3 52 13.4		Tatum
29.53692	12 24 06.74	−3 48 25.0		Urata
29.70046	12 24 01.71	−3 47 56.4		"
Apr. 1.88329	12 22 28.62	−3 38 37.4	13.1	Meyer
1.88656	12 22 28.71	−3 38 36.6	13.8	"

K. Endate (Kitami). 0.25-m $f/2.6$ Schmidt camera. Measurer K. Watanabe. Prediscovery observations.
O. Naranjo (Mérida). 1.0-m Schmidt. Independent discovery.
J. B. Tatum and D. D. Balam (Victoria). 0.25-m Schmidt.
T. Urata (Oohira). 0.25-m $f/3.4$ hyperboloid astrocamera + CCD.
E. Meyer and H. Raab (Linz). 0.3-m $f/5.2$ Schmidt-Cassegrain + CCD.

Attempts at orbit determination from the Mar. 15-Apr. 1 arc suggest that a parabolic solution is no longer viable, but the likely location of the object near the surface of Jupiter's sphere of influence—not to mention the near impossibility of measuring the object's center of mass—continues to make the unequivocal determination of an elliptical orbit extremely difficult. A very close encounter with Jupiter during 1992 continues to be a distinct possibility, the most viable such solutions having still smaller orbital eccentricities than in the example on *IAUC* 5726 and the Jupiter encounter earlier in the year. The heliocentric orbit below puts the object 0.007 AU from Jupiter on 1992 May 16 (tidal breakup presumably requiring an approach to 0.001 AU) and indicates that the object is at least temporarily in orbit about Jupiter and currently near apojove at a distance of 0.31 AU.

Epoch = 1993 Apr. 3.0 TT
T = 1997 Sept. 4.494 TT ω = 348°.427
e = 0.07169 Ω = 343.394 } 2000.0
q = 4.71659 AU i = 2.206
a = 5.08085 AU n° = 0.086060 P = 11.45 years

1993 April 3   *Brian G. Marsden*



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PERIODIC COMET SHOEMAKER-LEVY 9 (1993e)

Almost 200 precise positions of this comet have now been reported, about a quarter of them during the past month, notably from CCD images by S. Nakano and by T. Kobayashi in Japan and by E. Meyer, E. Obermair and H. Raab in Austria. These observations are mainly of the "center" of the nuclear train, and this point continues to be the most relevant for orbit computations. Orbit solutions from positions of the brighter individual nuclei will be useful later on, but probably not until the best data can be collected together after the current opposition period. At the end of April, computations by both Nakano and the undersigned were beginning to indicate that the presumed encounter with Jupiter (cf. *IAUC* 5726, 5744) occurred during the first half of July 1992, and that there will be another close encounter with Jupiter around the end of July 1994. Computations from the May data confirm this conclusion, and the following result was derived by Nakano from 104 observations extending to May 18:

Epoch = 1993 June 22.0 TT
T = 1998 Apr. 5.7514 TT ω = 22°.9373
e = 0.065832 Ω = 321.5182 } 2000.0
q = 4.822184 AU i = 1.3498
a = 5.162007 AU n° = 0.0840381 P = 11.728 years

This particular computation indicates that the comet's minimum distance Δ_J from the center of Jupiter was 0.0008 AU (i.e., within the Roche limit) on 1992 July 8.8 UT and that Δ_J will be only 0.0003 AU (Jupiter's radius being 0.0005 AU) on 1994 July 25.4.

As noted on *IAUC* 5726, the positions of the ends of the nuclear train can be satisfied by varying the place in orbit at the time of the 1992 encounter and considering the subsequent differential perturbations. Using the above orbital elements, the undersigned notes that the train as reported on *IAUC* 5730 corresponds to a variation of ±1.2 *seconds*. Separation can be regarded as an impulse along the orbit at encounter, although the velocity of separation (or the variation along the orbit) depends strongly on the actual value of Δ_J. At the large heliocentric distances involved any differential nongravitational acceleration must be very small, as Z. Sekanina, Jet Propulsion Laboratory, has also noted. Extrapolation to shortly before the 1994 encounter indicates that the train will then be ∼ 20′ long and oriented in p.a. 61°-241°, whereas during the days before encounter the center of the train will be approaching Jupiter from p.a. ∼ 238°.

1993 May 22   *Brian G. Marsden*

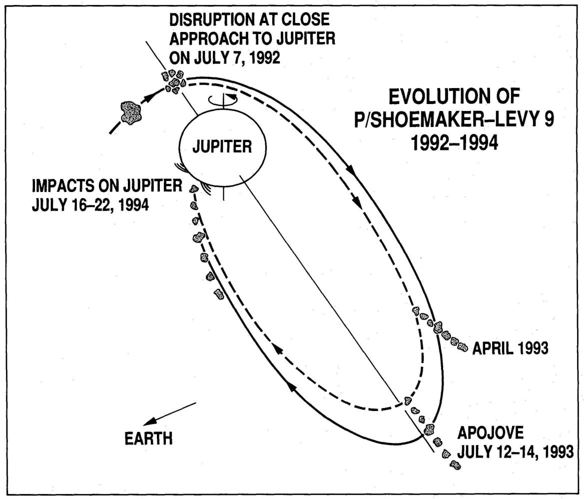
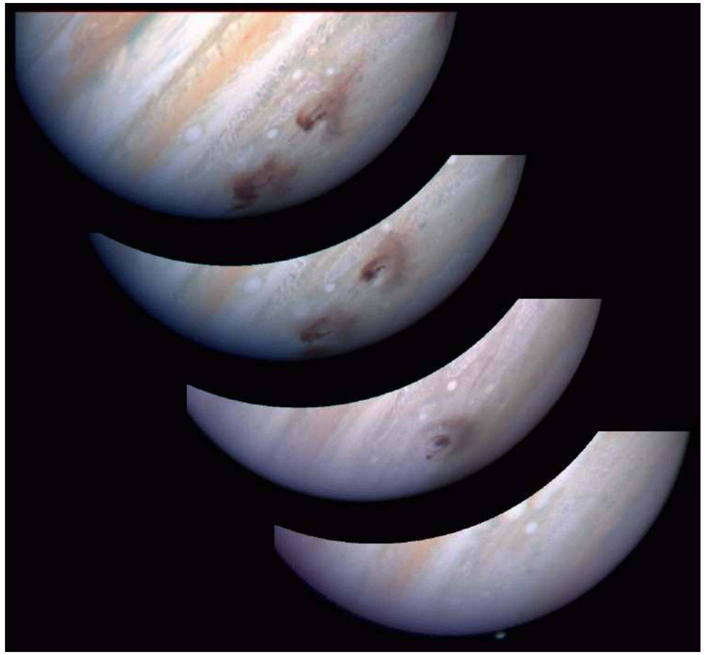
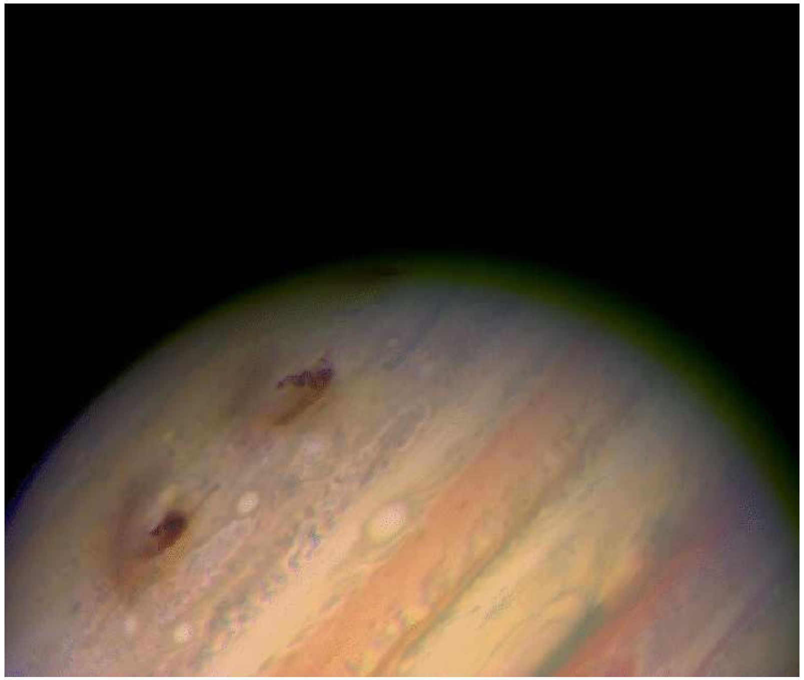


Fig. 9. Schematic representation of the tidal breakup of the parent nucleus of P/Shoemaker–Levy 9 in July 1992, the orbital evolution of its fragments, and their collision with Jupiter in July 1994. It should be remembered that the orbital dimensions and the sizes of Jupiter and the fragment chain are not drawn to scale. The apojove distance in July 1993 was in reality ~520 times the perijove distance in July 1992

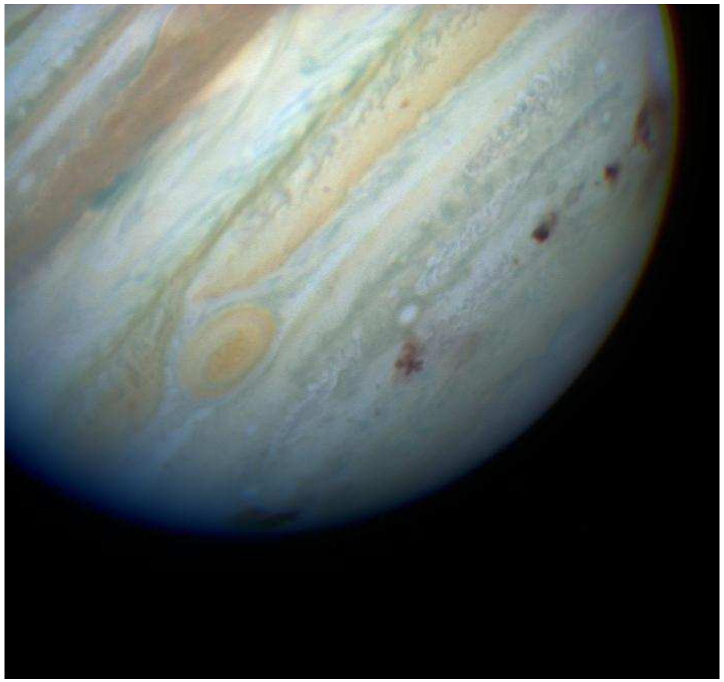
Sekanina et al. (1994, A&A 289, 607)



Evolution of impact G: bottom to top: 18 July 1994, 5' after impact of fragment (plume!), until 5 days after the impact).



HST: Impact of fragments D and G. Outer ring: $d \sim 12000$ km (Earth!).



HST image of Jupiter after the impacts

Sungrazers

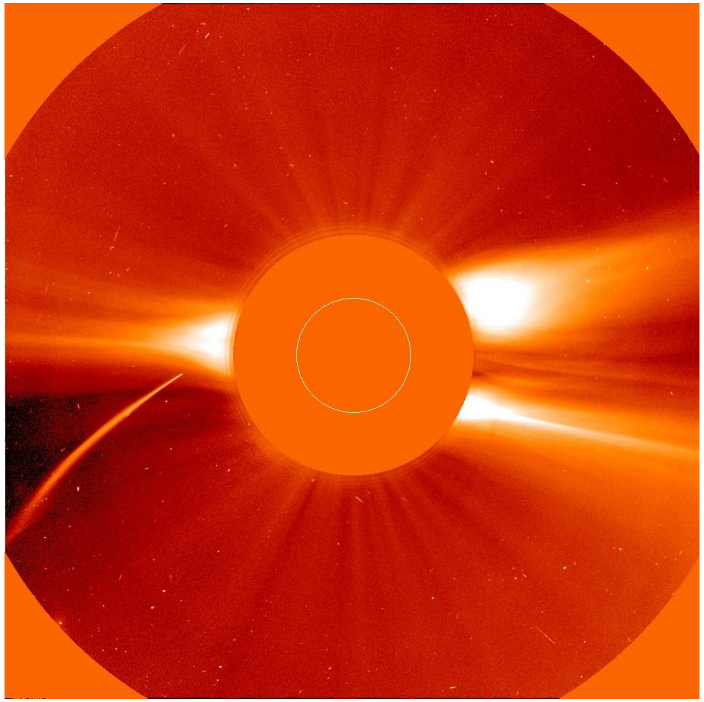
Sungrazing comets: . . . the unlucky ones, members of the Kreutz group of comets, which come within ~50000 km of the Sun.

Named after Heinrich Kreutz, who discovered these comets in the late 1800s.

Until 1979: 9 comets known.

Since then: solar observations from satellites, more comets found.

Since 1996: 1206 sungrazers discovered with instruments onboard ESA's SOHO spacecraft.

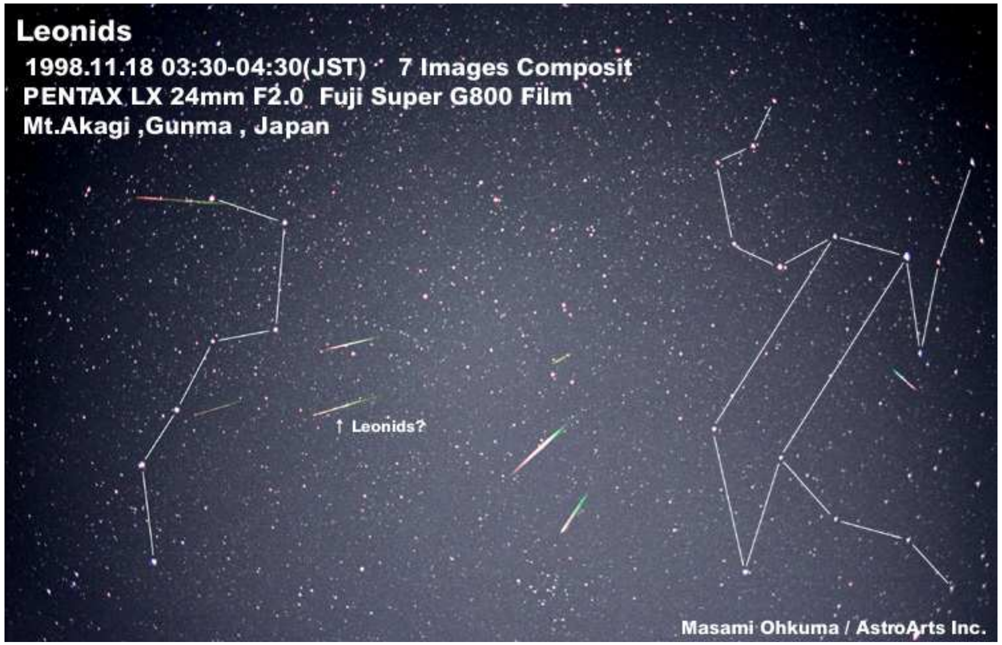


Sungrazers

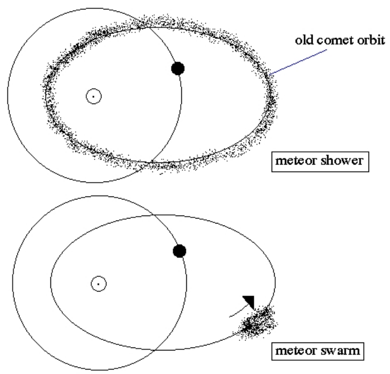
MOVIE TIME:

- `Hyakutake.mpg`: Perihelion passage of P/Hyakutake. Note dust tail and plasma tail!
- `cometM.mpg`: perihelion passage of comet P/Macholz
- `c2002v1.mpg`: perihelion passage of another comet in 2002
- `C3_2comets_CME.mpg`: two comets hitting the sun, followed by an (unrelated!) coronal mass ejection

Meteors

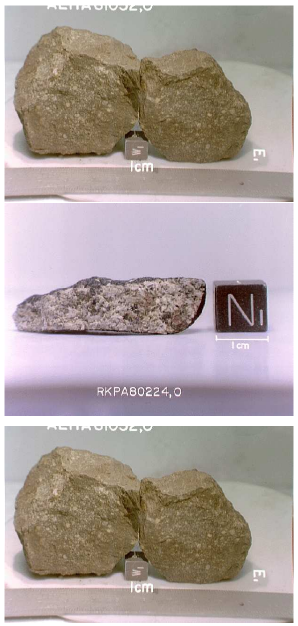


Origin of meteor swarms



- ≈25 Mio./day hit Earth's atmosphere.
- most burn up
- ≈1 Mio. kg/day to Earth's surface.
- large ones break into pieces, are ablated, but reach the surface as meteorites
- origin: debris of comets: dust tails
- showers/swarms when earth crosses a comet's orbit named after constellation of radiant
- e.g., Leonids due to 55P/Tempel-Tuttle (mid of November).

Meteorites



three major types:

- Chondrites: most common, stone, radiometric dating: age=4.55 billion years
- Pallasites: stone with metals
- iron meteorites: 13 subclasses: iron-nickel allows

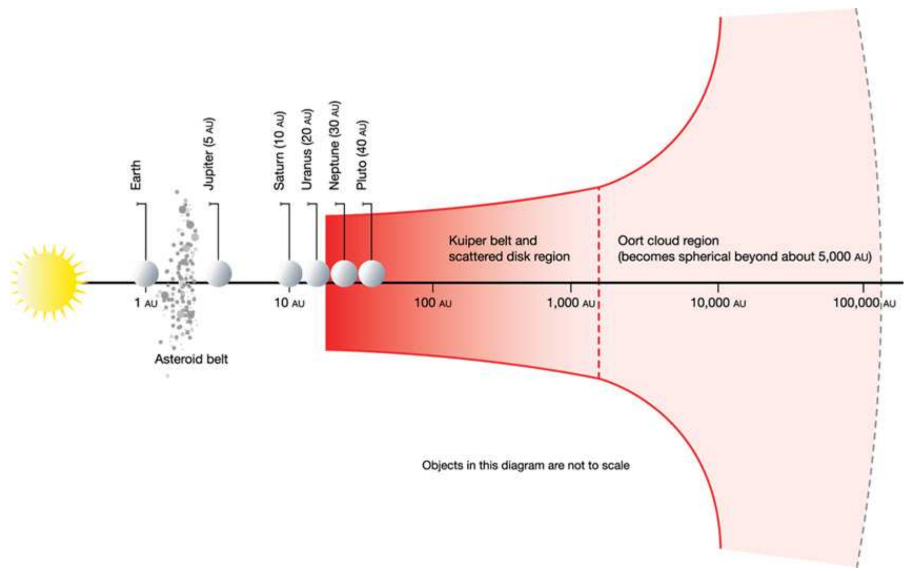
Origin of Comets

Long period comets: $P \geq 200$ years, have very eccentric orbits with huge semi-major axes, all angular momenta and inclinations observed.

Jan Oort (1950) suggested the presence of a large cloud of comets at *huge* distances around the Sun (Oort cloud).

Formal definition: Oort cloud is ensemble of all comets with semi-major axis $a \geq 10^4$ AU; estimated content $\sim 10^{11}$ to 10^{12} objects, total mass 1–50 Earth masses, temperature 5–10 K.

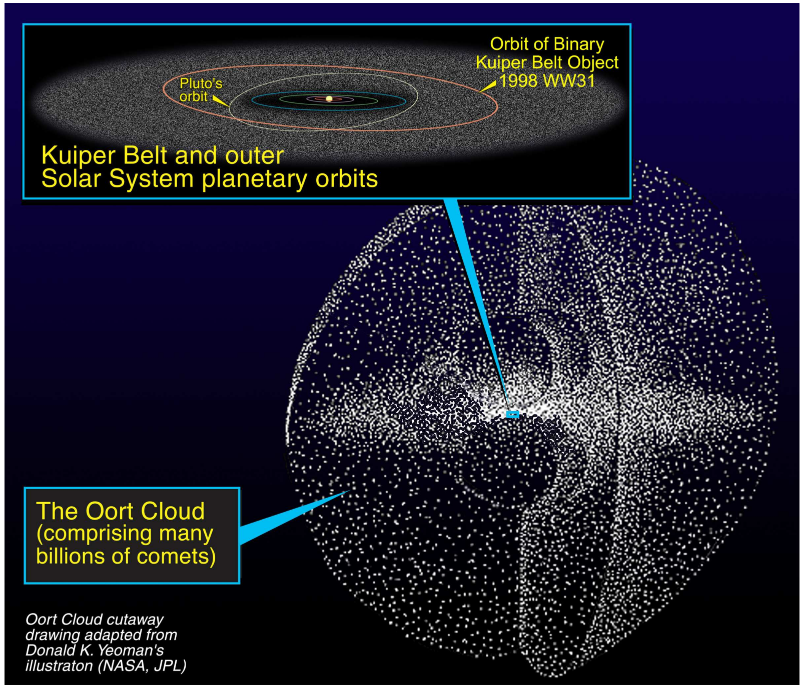
Long period comets originate in Oort cloud, orbits are disturbed by passing stars or Giant Molecular Clouds.



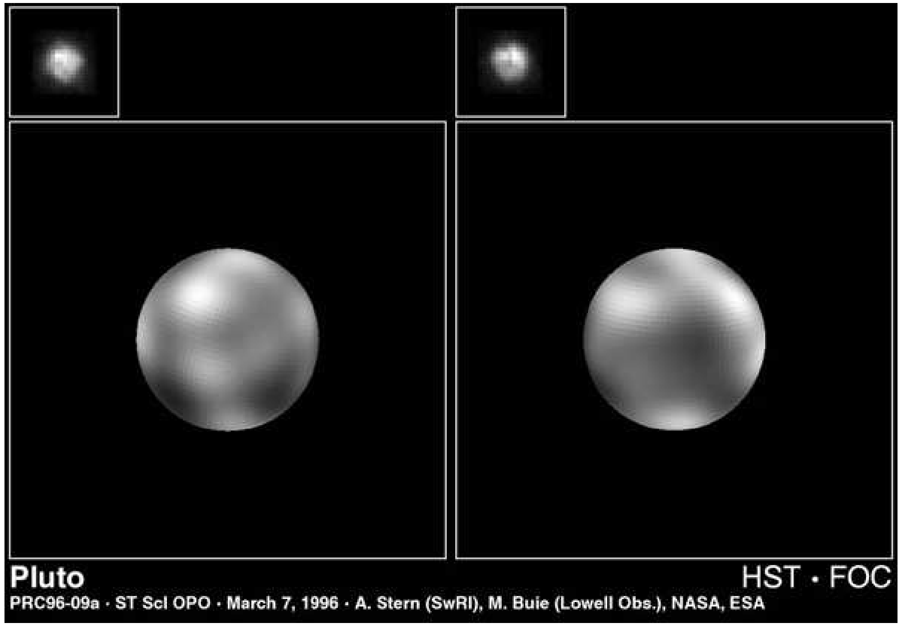
S.A. Stern (2003, Nature 424, 639–642)

short period comets: $P < 200$ years: show angular momenta similar to planets, mainly found in plane of solar system.

$\Longrightarrow$ probably from Kuiper belt, high collision rates there fragment objects, leading to cometary debris.

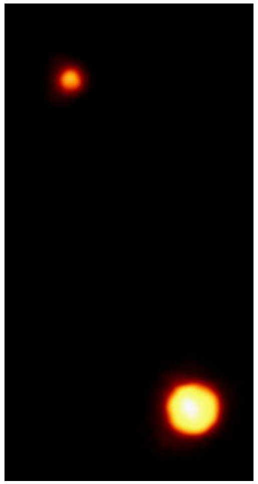


NASA/ A. Feild(STScI)



Transneptunians

Pluto - the dwarf planet

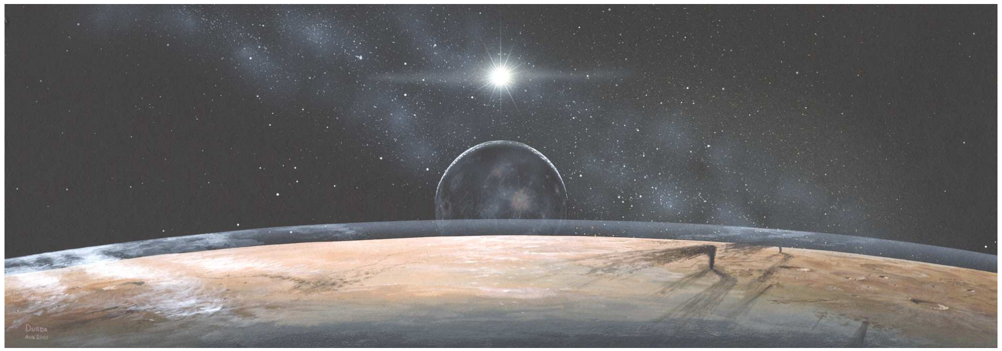


NASA/ESA HST

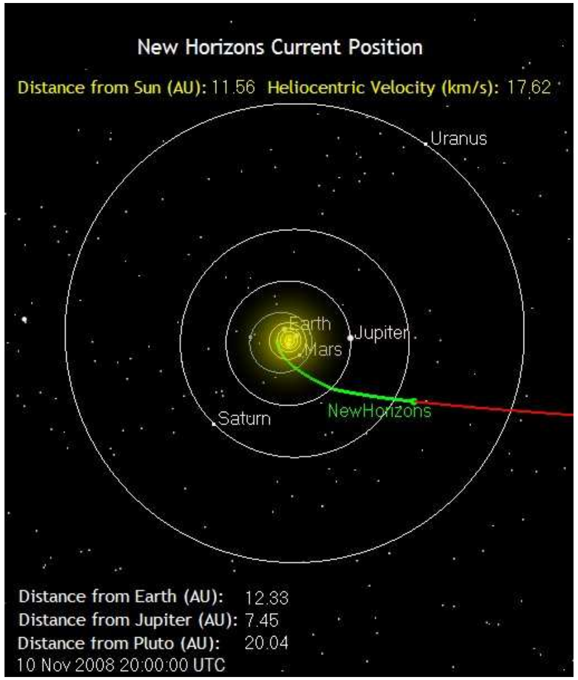
Pluto/Charon:

- discovered 1930/1978
- double system (Pluto: $D = 2320$ km, Charon: $D = 1270$ km)
- icy surface, probably cratered
- one of the largest transneptunian objects, member of the Kuiper belt

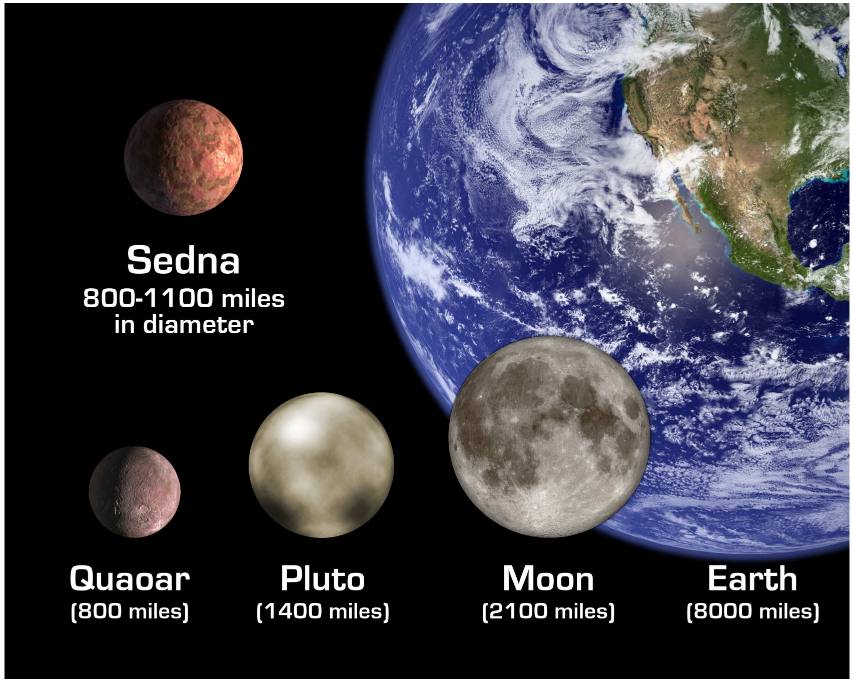
Kuiper belt: similar to asteroid belt, $>$70000 objects outside Neptune in 30–50 AU region; largest further members currently known: Quaoar ($D = 1200 \pm 200$ km), Ixion ($D = 1060 \pm 165$ km), Varuna ($D = 900 \pm 140$ km), 2002 AW197 ($D = 890 \pm 120$ km), see `http://www.ifa.hawaii.edu/faculty/jewitt/kb.html`



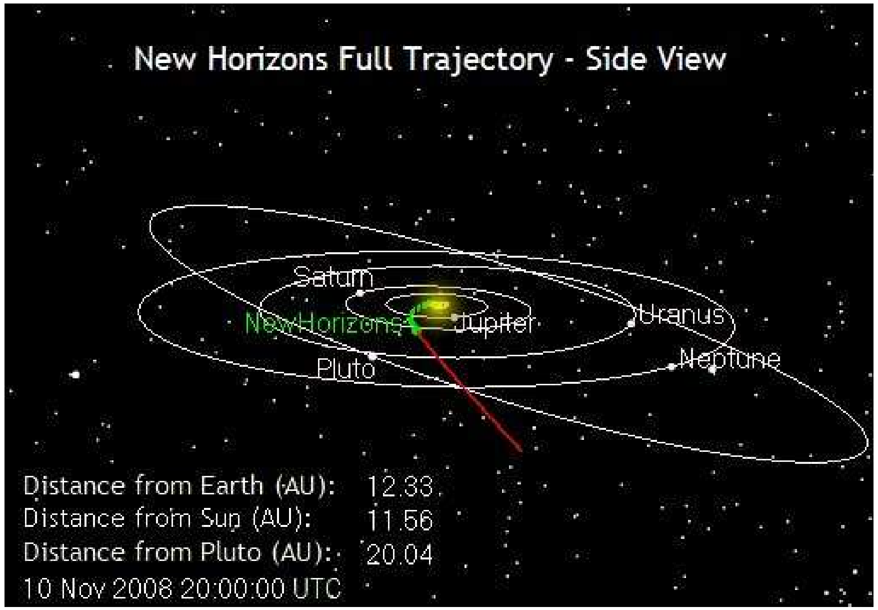
Artist's impression of Pluto and Charon (D. Durda, SWRI)

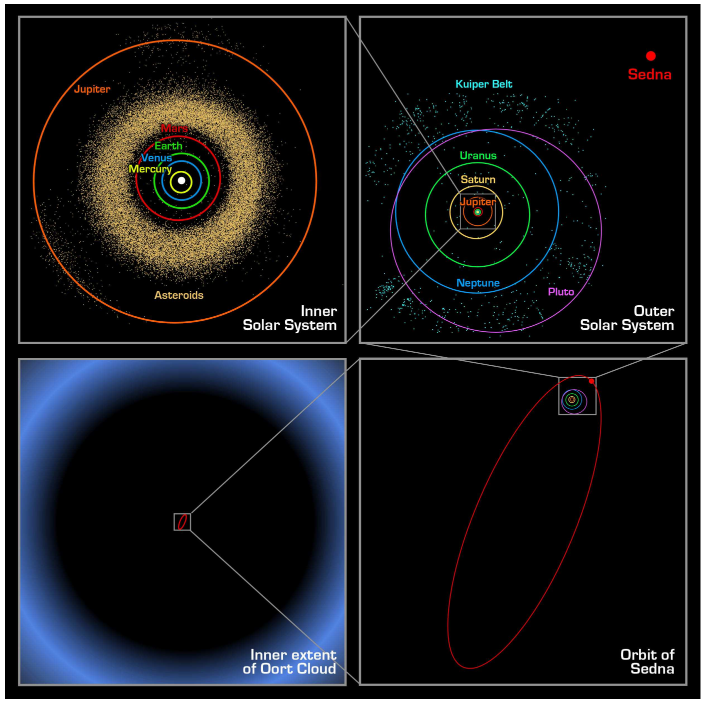


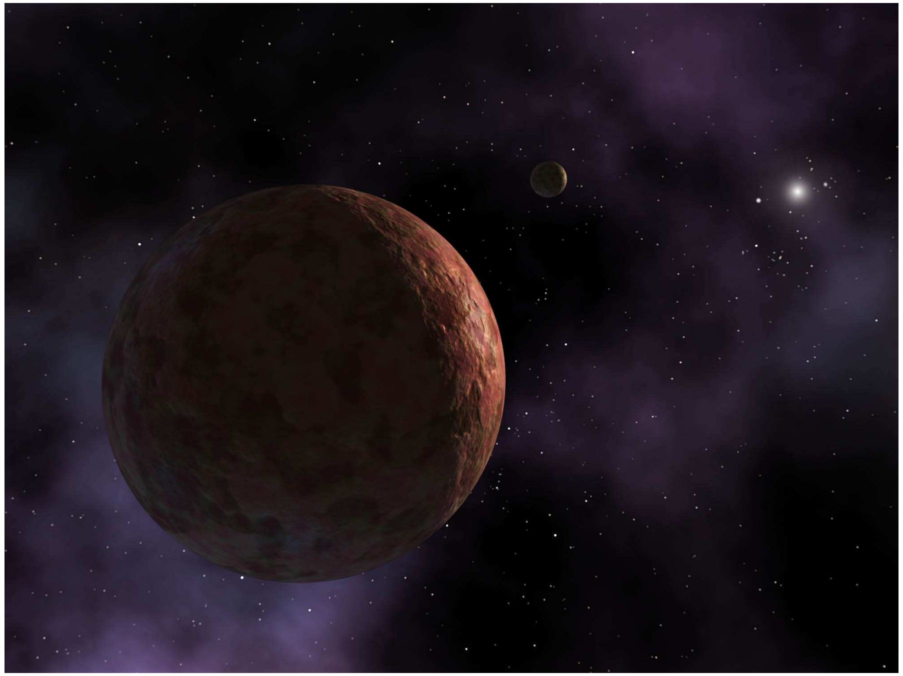
New Horizons: NASA Mission to Pluto and beyond launched 2006 January 19,
2007 February: Jupiter gravity assist,
2015 July: Flyby at Pluto and Charon,
Kuiper Belt mission until 2020



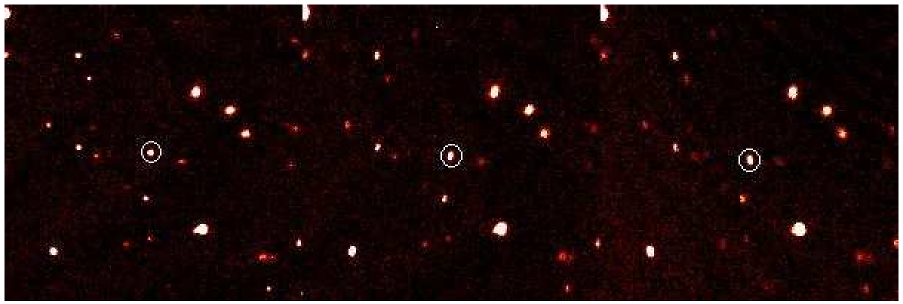
R. Hurt (SSC-Caltech)







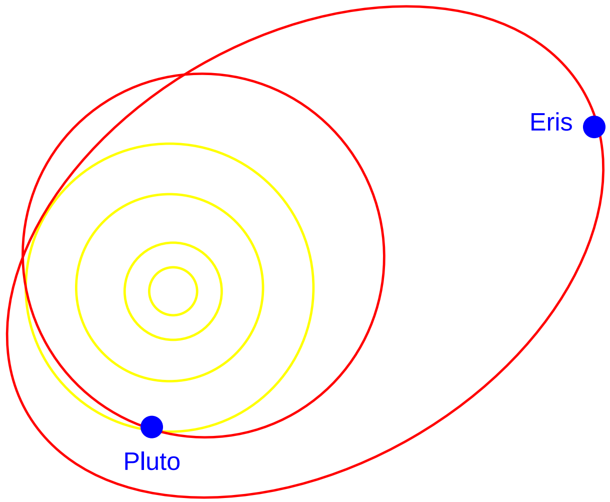
Viewing inwards from Sedna (NASA/JPL)



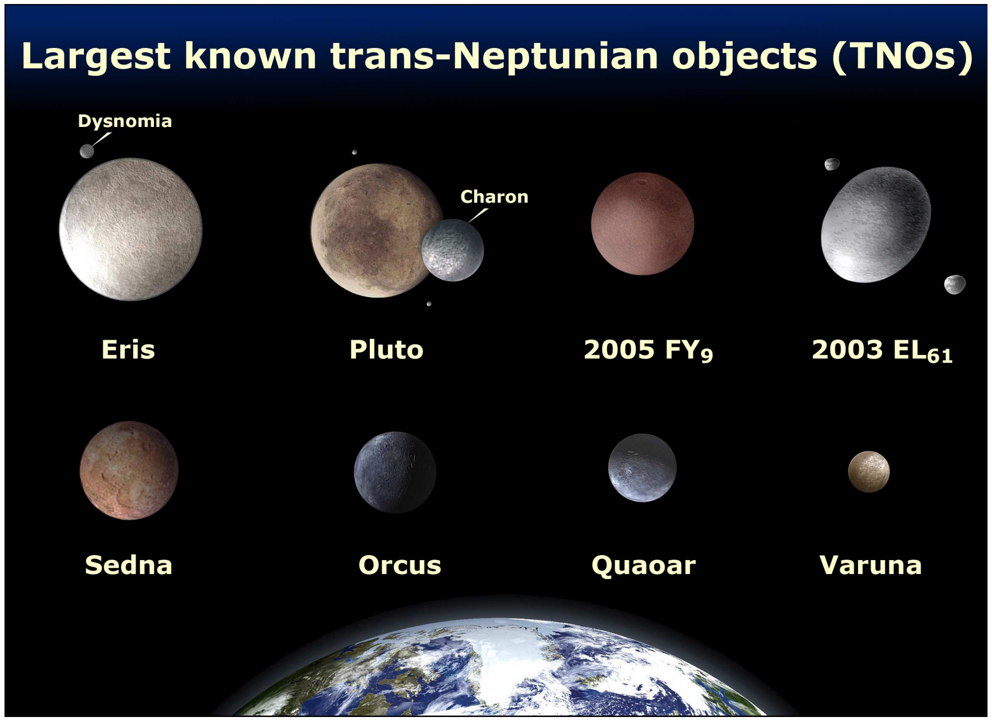
Discovery images of the dwarf planet Eris. The three images were taken 1 1/2 hours apart on the night of 2003 October 21st. Eris can be seen to move very slowly across the sky over the course of 3 hours. (M. Brown et al. Caltech)

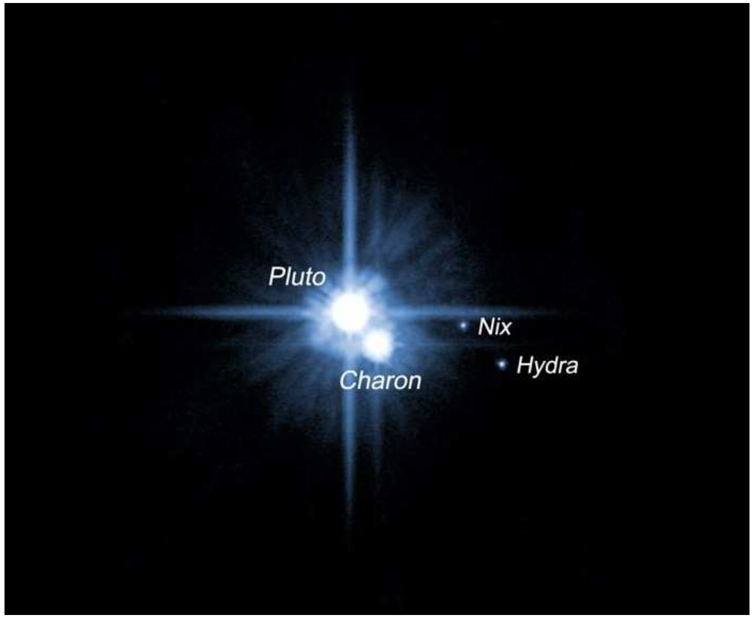
Eris (2003 UB_{313}): discovered 2005: distance $\sim$100 AU, brightness similar to Pluto

$\Longrightarrow$ larger than Pluto, unless it is 100% reflective (unlikely)!

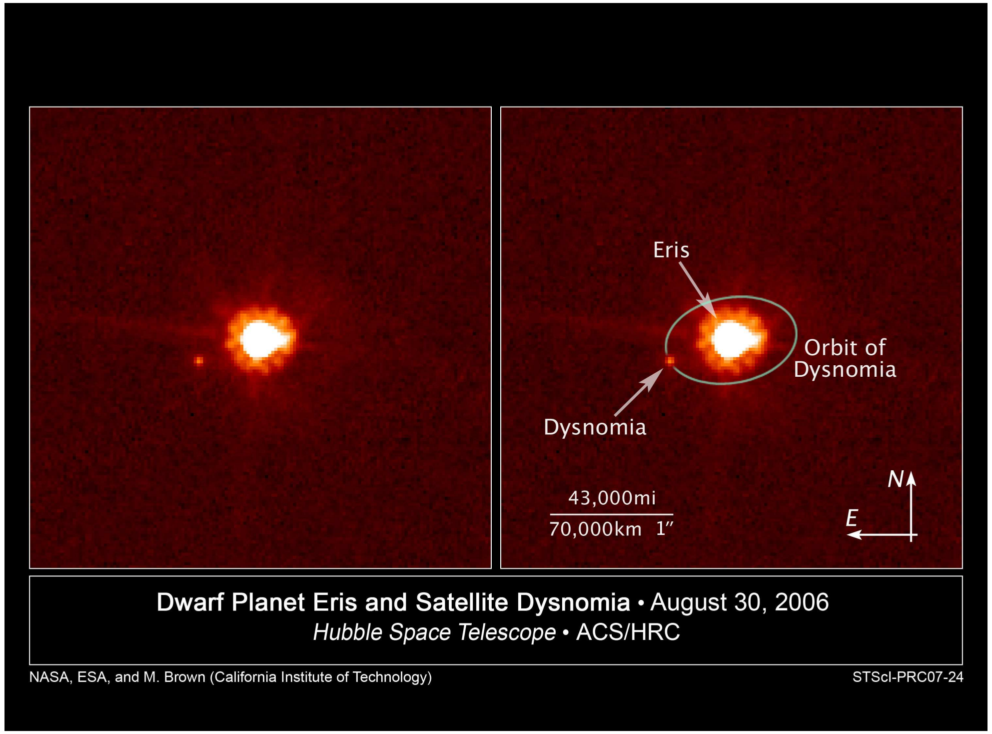


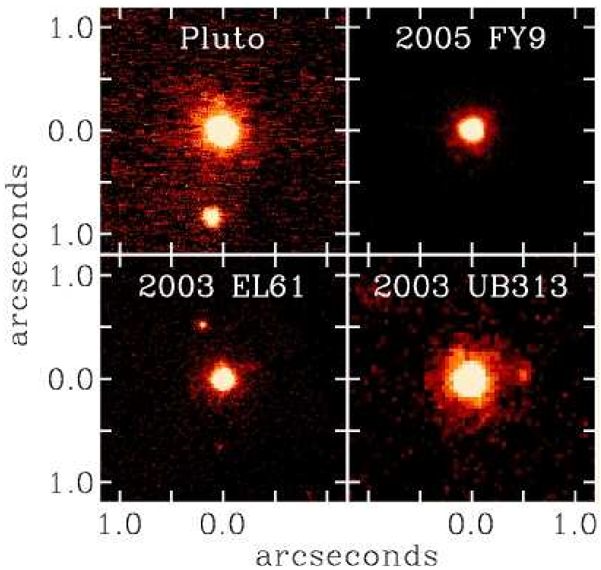
after M. Brown et al. (Caltech)



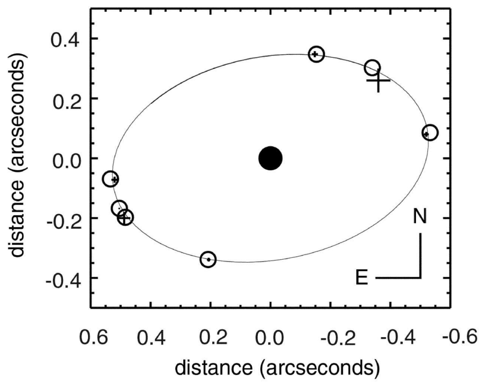


3 moons of Pluto:
http://antwrp.gsfc.nasa.gov/apod/ap060624.html

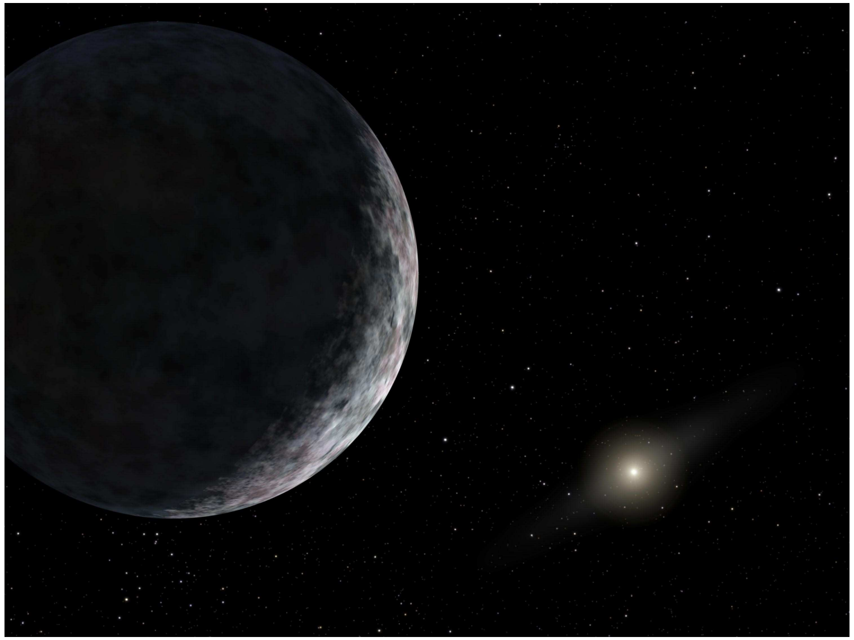




The orbit of Dysnomia around Eris:



- circular orbit
- Period $P = 15.773$ days
- Orbital radius: $R = 37400$ km (Brown & Schaller, Science Vol 316, 15 June 2007)
- Homework:
  - Determine the mass of Eris
  - Diameter of Eris: 2400 km, determine the density of Eris
  - Compare mass and density of Eris with those of Pluto



Eris: View of the Solar System

(drawing courtesy M. Brown et al./NSF/NASA)