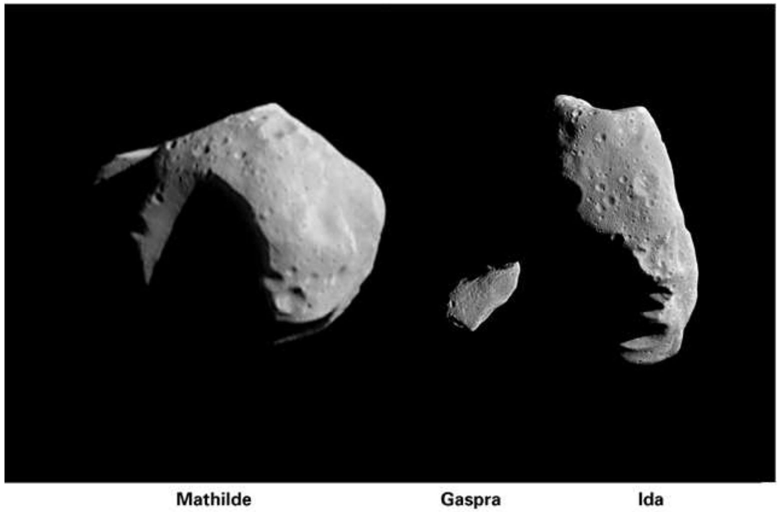
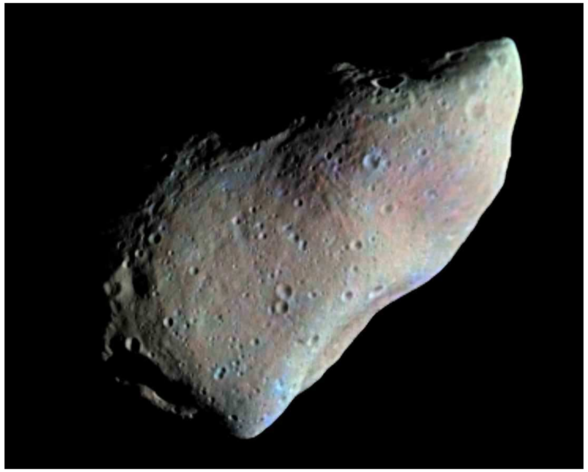
Small Solar System Bodies: Asteroids, Comets, and Transneptunians



Size comparison of several asteroids (NASA).

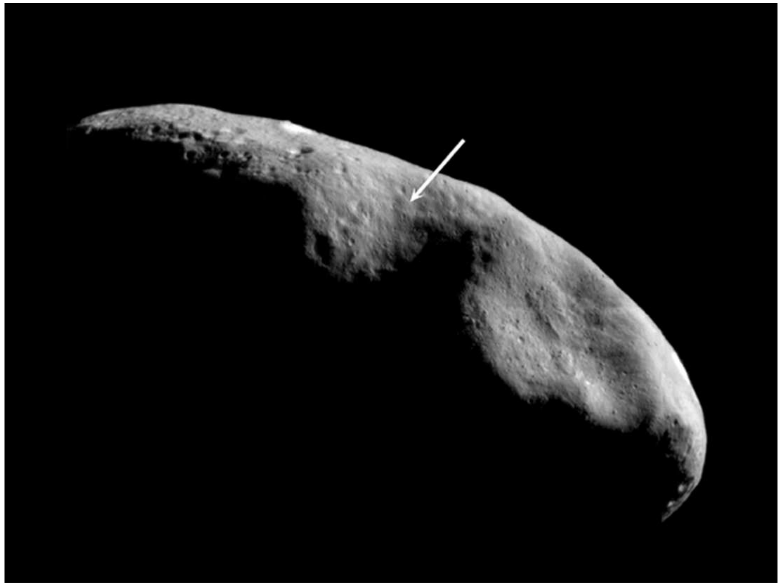
Several asteroids surveyed by interplanetary probes (Mathilde: NEAR Shoemaker; Gaspra: Galileo)



951 Gaspra (NASA)

Asteroids: Minor planets somewhere between Mercury and Neptune, diameters <1000 km

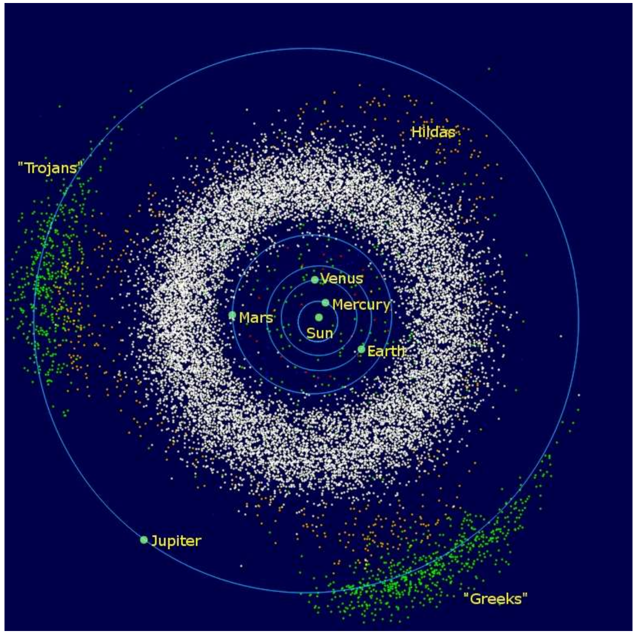
First discovery (Piazzi) in 1801 (Ceres, diam. 1000 km)
Today >100000 known, only 7 with diameters >300 km
Total mass $\sim$0.5% of Earth (4% of the Moon), of which $\sim$30% in Ceres, 75% are C-type (carbonaceous), 17% S-type (silicaceous), and 8% M-type (metallic) asteroids.



2001 Feb 12: NEAR lands on Eros

MOVIE TIME: `043_MSI_Final_Descent_DSL.rm`

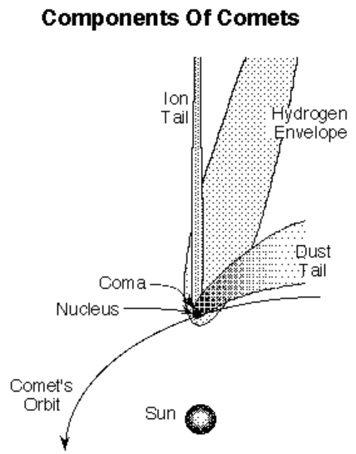
153P/Ikeya-Zhang (©M. Jäger)



Wikipedia

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

Structure, III



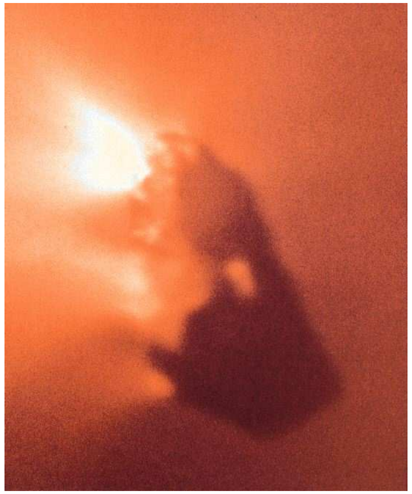
NASA

Major components of a comet:

- Nucleus: "Dusty Snowball", 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.

Halley, I

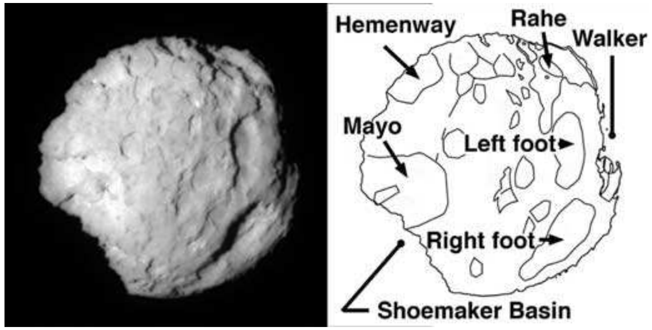


ESA

1P/Halley:

- Longperiodic comet (76 year orbit)
- 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.

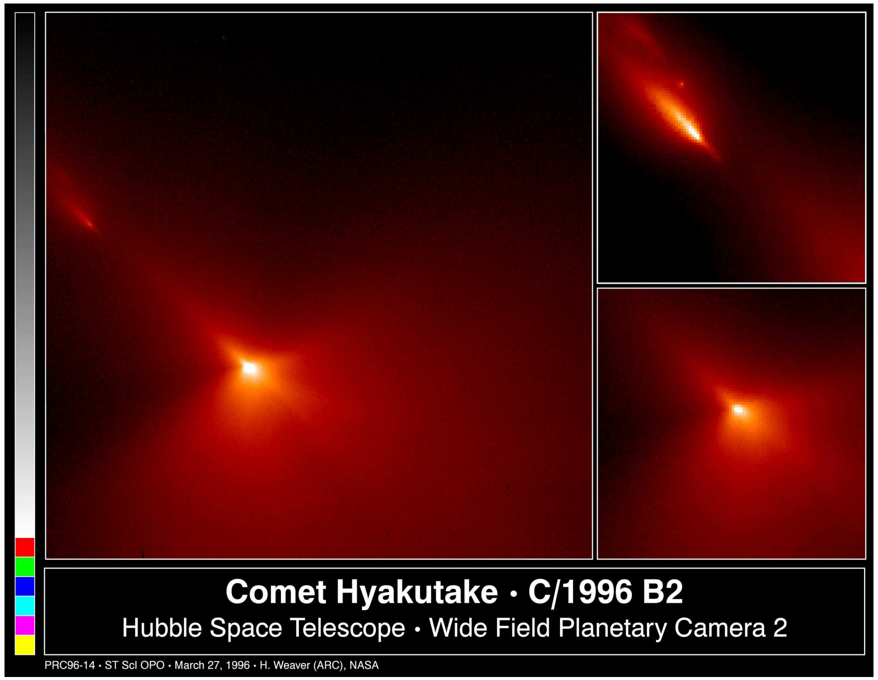
Comet Wild 2, I

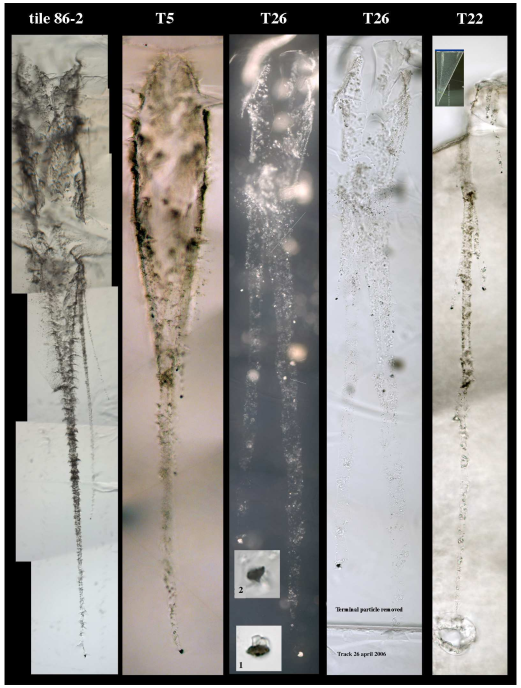


NASA, stardust mission, size ∼5 km

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) $\Longrightarrow$ Material has not been processed by Sun before sample return.





Tracks by particles from comet Wild-2 in the aerogel onboard Stardust.
Currently being analyzed by large team of scientists, results expected end of 2006.

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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 $\sim 1'$ 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 $\sim 47''$ in length and $\sim 11''$ in width, aligned along p.a. 80°-260°. At least five discernible condensations were visible within the train, the brightest being $\sim 14''$ 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 $\sim 4°$ 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 $V = 20.3 \pm 0.1$ 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:

$$T = \text{1994 Aug. 3.441 TT} \qquad \omega = 300^\circ.459$$
$$\Omega = 344.563 \quad (2000.0)$$
$$q = 2.36996 \text{ AU} \qquad i = 2.322$$

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

$$T = \text{1988 Dec. 5.767 TT} \qquad \omega = 43^\circ.253$$
$$e = 0.18714 \qquad \Omega = 347.657 \quad (2000.0)$$
$$q = 3.91756 \text{ AU} \qquad i = 2.684$$

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.

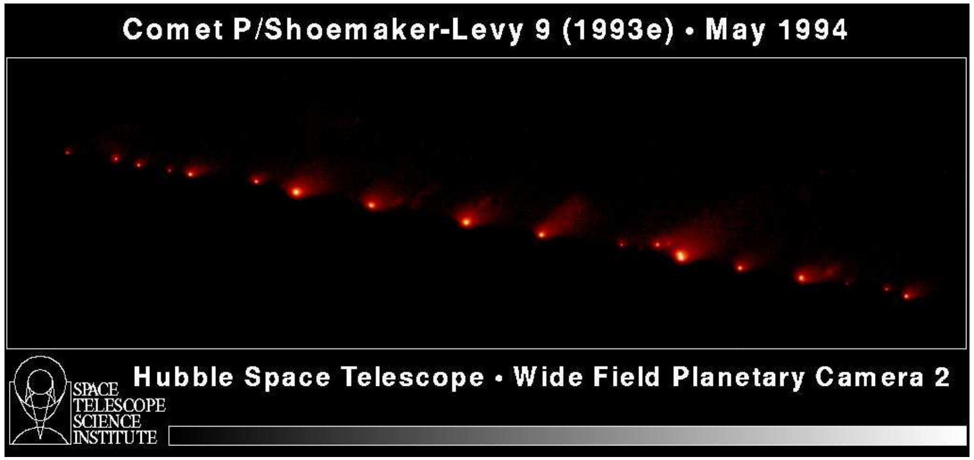
$$\text{Epoch} = \text{1993 Mar. 14.0 TT} \qquad u = 359^\circ.468$$
$$\Omega = 187.896 \quad (2000.0)$$
$$a = 42.451 \text{ AU} \qquad i = 8.029$$

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	$12^h30^m52^s.17$	$-4^\circ28'12''.3$	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

$$\begin{array}{lll} T = 1997\ \text{Sept.}\ 4.494\ \text{TT} & \omega = 348^\circ.427 & \\ e = 0.07169 & \Omega = 343.394 & \Big\}2000.0 \\ q = 4.71659\ \text{AU} & i = 2.206 & \end{array}$$

$$a = 5.08085\ \text{AU} \qquad n^\circ = 0.086060 \qquad P = 11.45\ \text{years}$$

1993 April 3 *Brian G. Marsden*

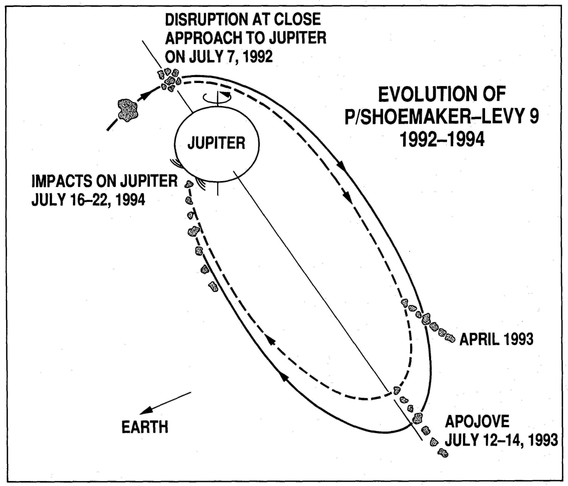

Fig. 9. Schematic representation of the tidal breakup of the parent nucleus of P/Shoemaker–Levy 9 in July 1992, the orbital evolution of its fragments, and their collision with Jupiter in July 1994. It should be remembered that the orbital dimensions and the sizes of Jupiter and the fragment chain are 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)

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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

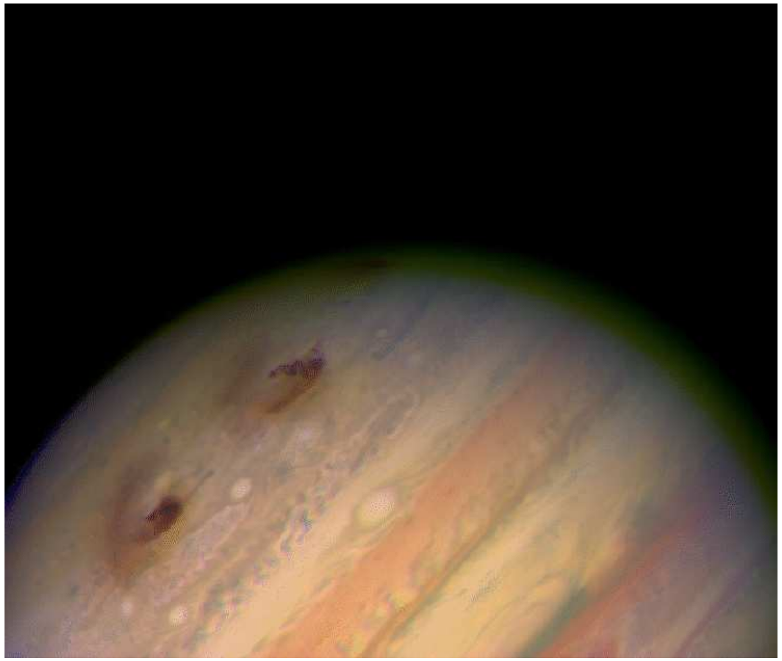
$$\begin{array}{lll} T = 1998\ \text{Apr.}\ 5.7514\ \text{TT} & \omega = 22^\circ.9373 & \\ e = 0.065832 & \Omega = 321.5182 & \Big\}2000.0 \\ q = 4.822184\ \text{AU} & i = 1.3498 & \end{array}$$

$$a = 5.162007\ \text{AU} \qquad n^\circ = 0.0840381 \qquad P = 11.728\ \text{years}$$

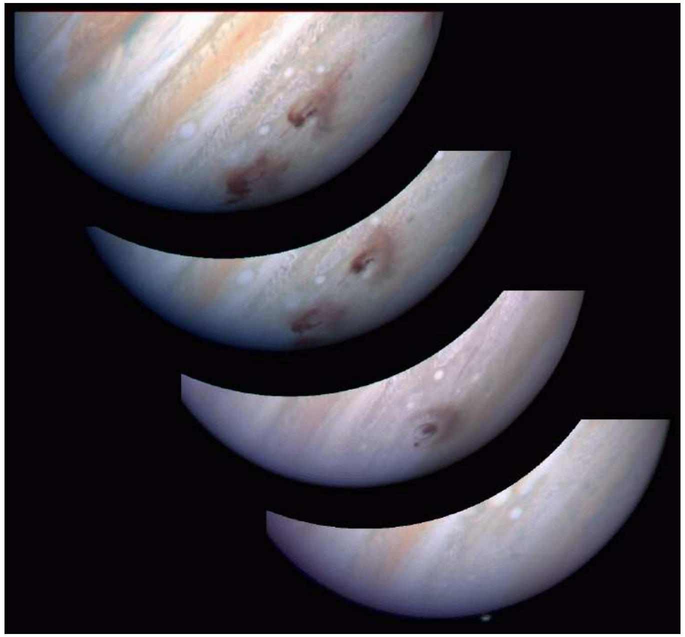
This particular computation indicates that the comet's minimum distance Δ_J from the center of Jupiter was 0.0008 AU (i.e., within the Roche limit) on 1992 July 8.8 UT and that Δ_J will be only 0.0003 AU (Jupiter's radius being 0.0005 AU) on 1994 July 25.4.

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 $\sim 20'$ 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*



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



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

Sungrazers, II

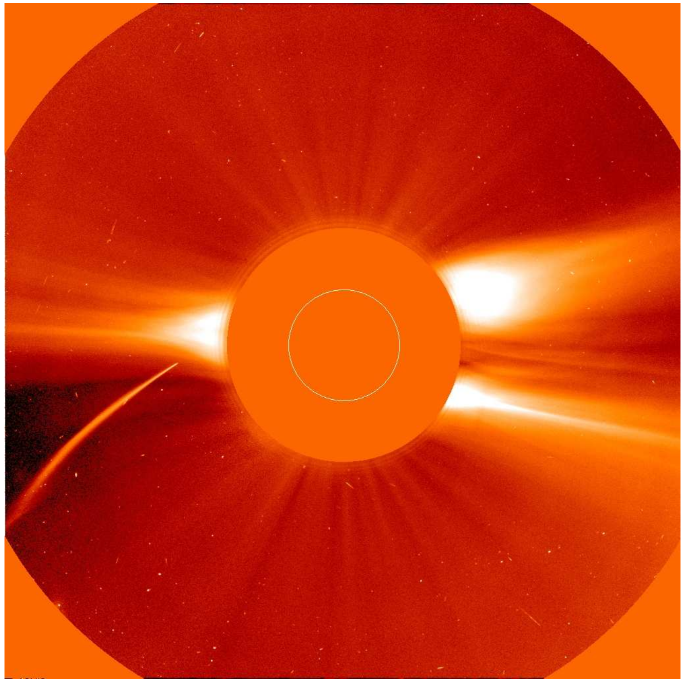
Sungrazing comets: . . . the unlucky ones, members of the Kreutz group of comets, which come within $\sim$50000 km of the Sun.

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.



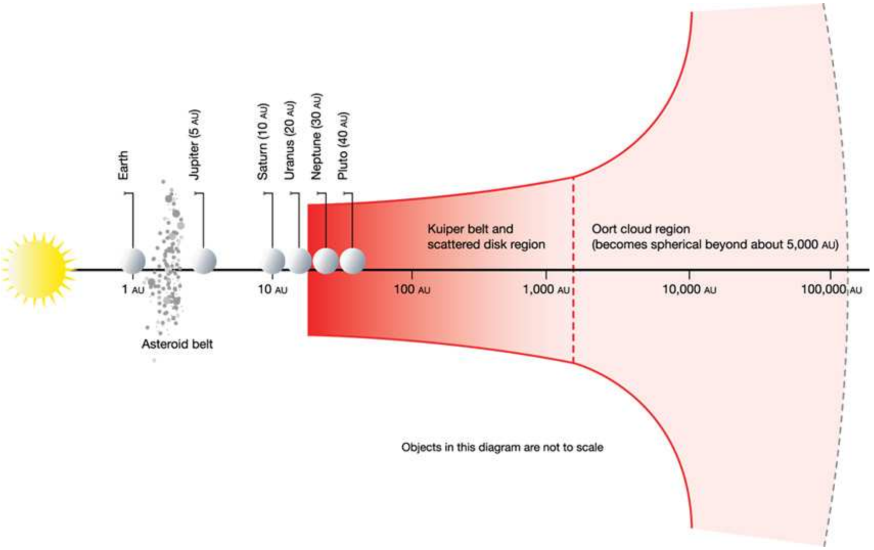
Origin of Comets, I

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.

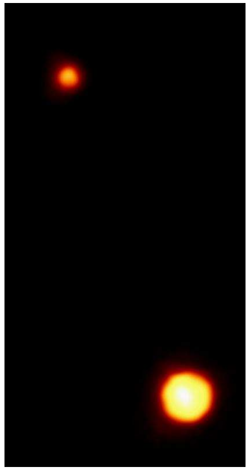
Long period comets originate in Oort cloud, orbits are disturbed by passing stars or Giant Molecular Clouds.



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.

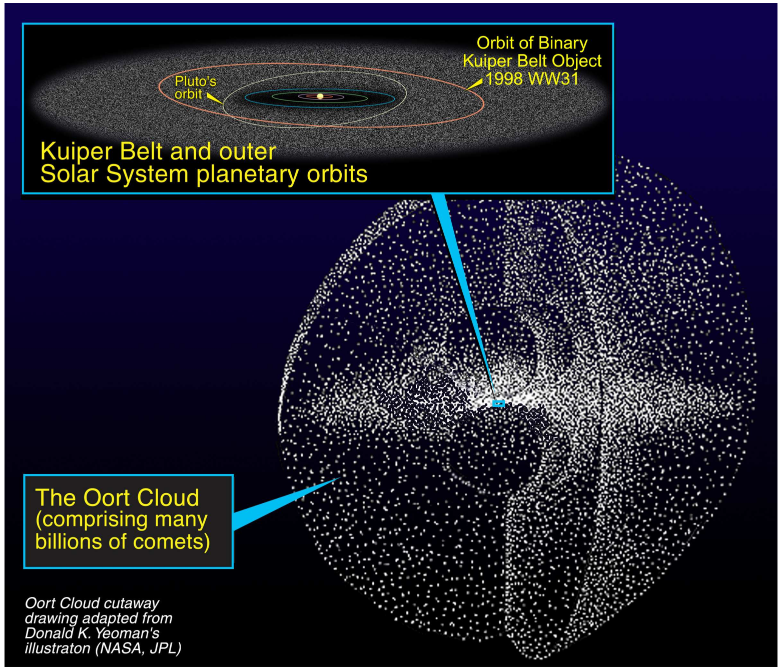


NASA/ESA HST

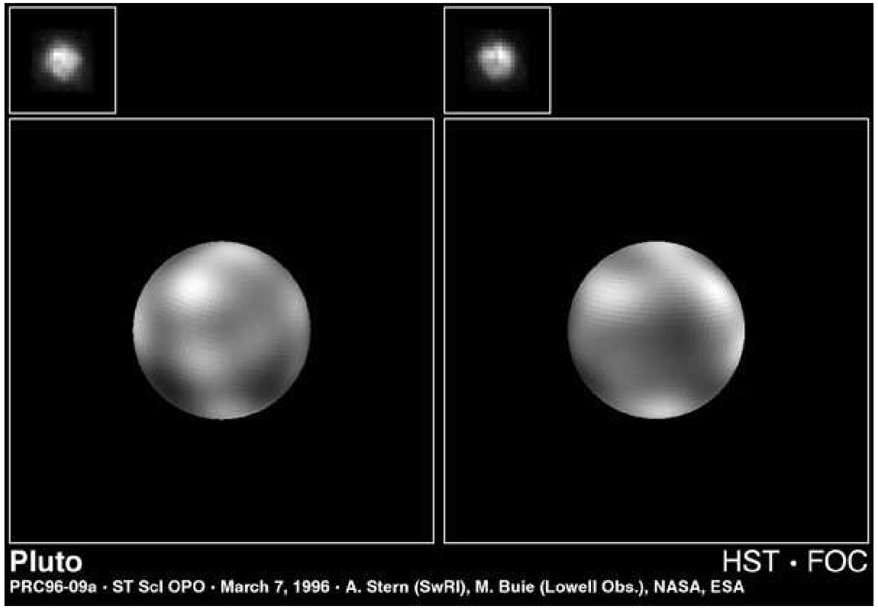
Pluto/Charon:

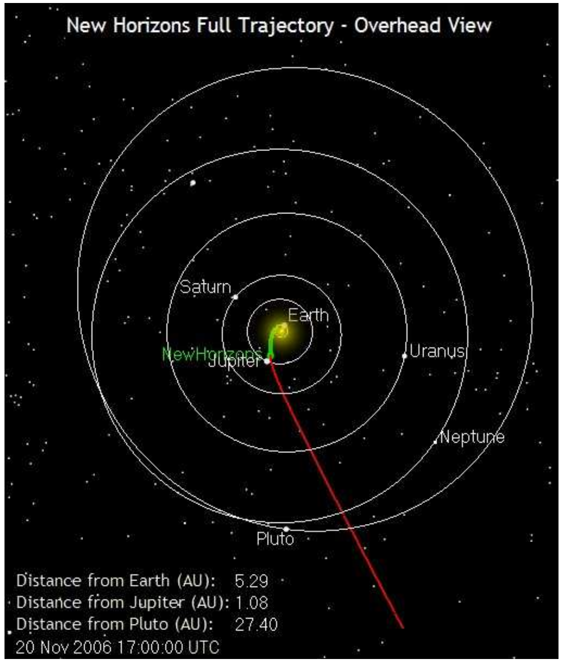
- discovered 1930
- double system (Pluto: $D = 2320$ km, Charon: $D = 1270$ km), 2 smaller moons
- icy surface, probably cratered
- one of the largest transneptunian objects, member of the Kuiper belt

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`

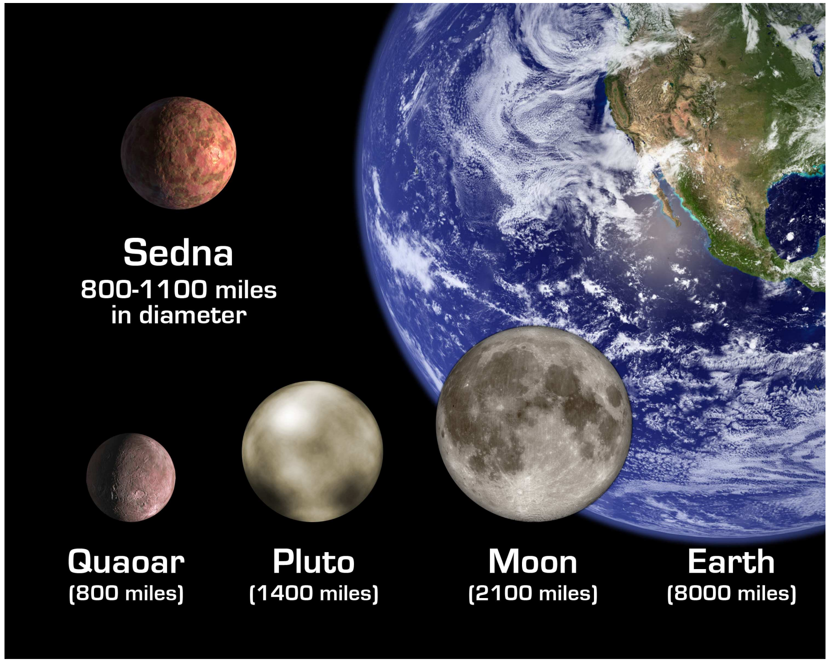


NASA/ A. Feild(STScI)

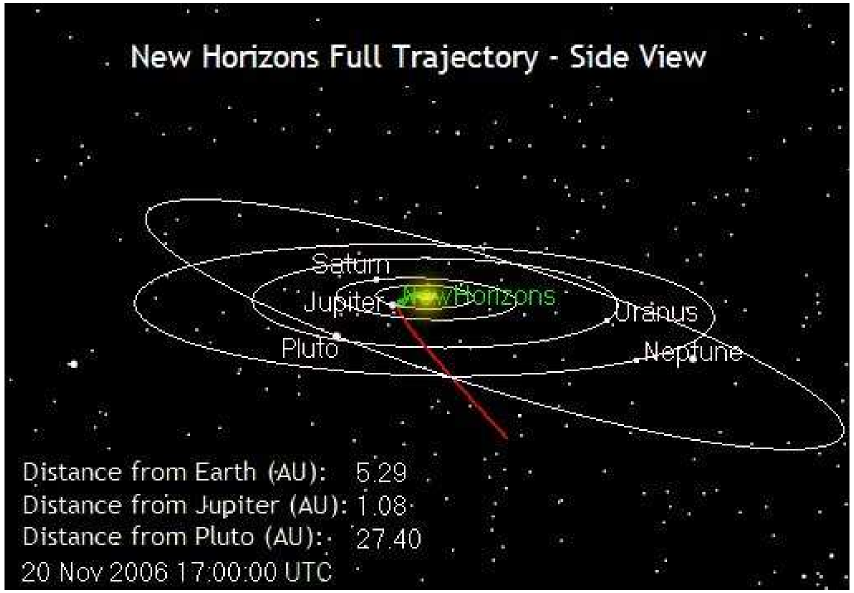


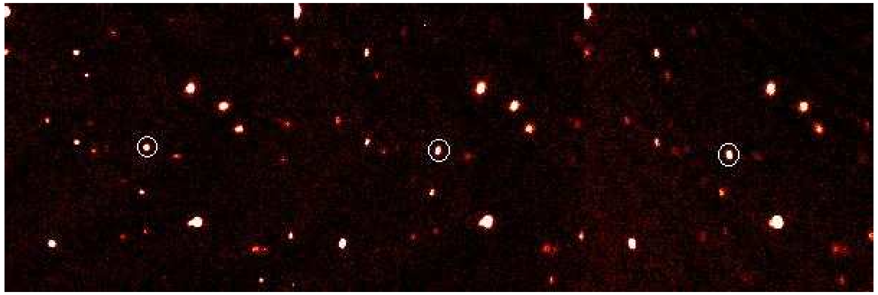


New Horizons: NASA Mission to Pluto and beyond launched 2006 January 19, 2007 February: Jupiter gravity assist, 2015 July: Flyby at Pluto and Charon, Kuiper Belt mission until 2020



R. Hurt (SSC-Caltech)

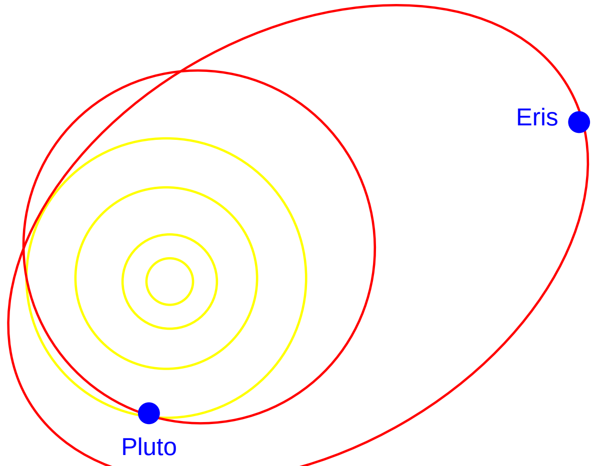




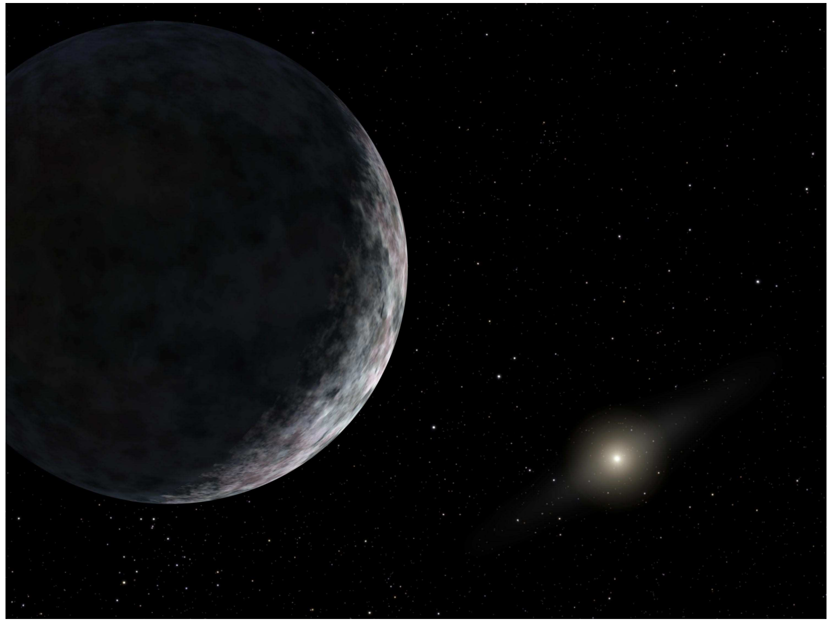
M. Brown et al. (Caltech)

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

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

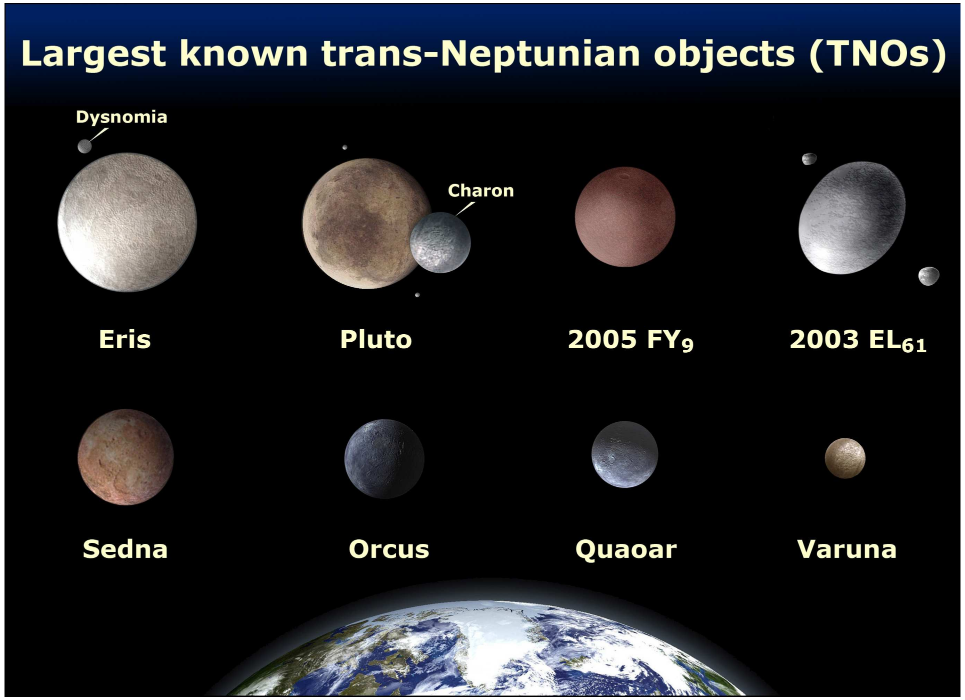


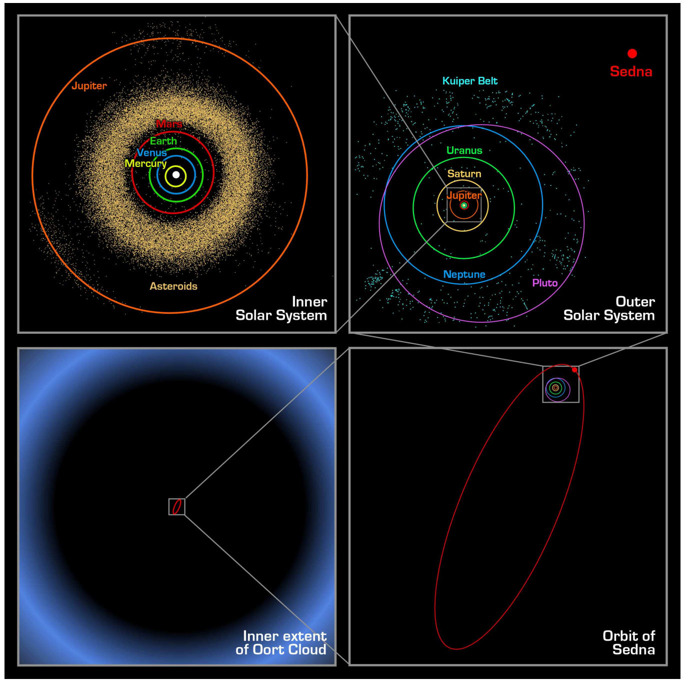
after M. Brown et al. (Caltech)

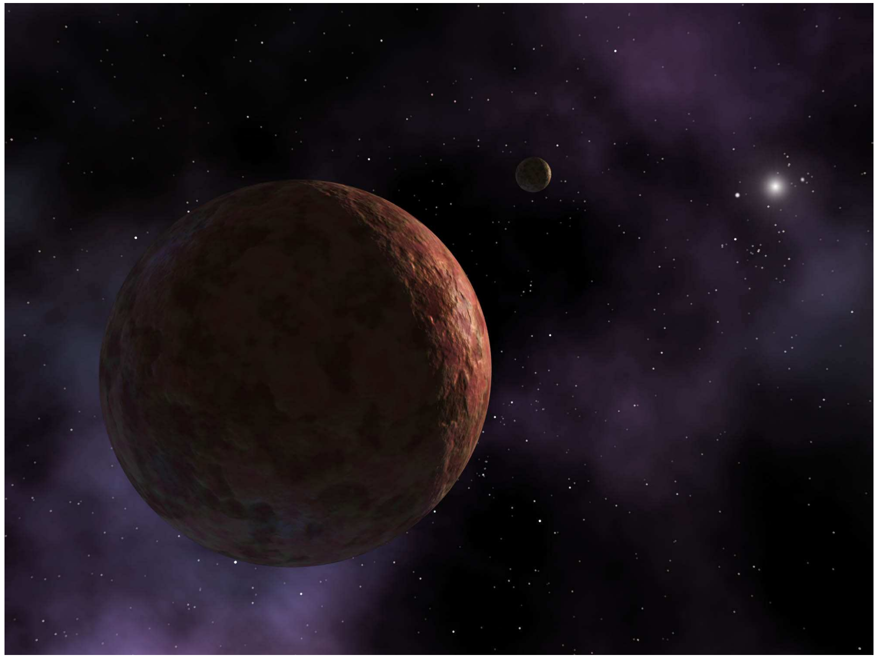


Eris: View of the Solar System

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







Viewing inwards from Sedna (NASA/JPL)