Close Encounters with Asteroids and Comets: New Insights from Dawn to Galileo*

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Abstract

The recent visits, impacts, sampling and close-up photography of asteroids and comets have revealed complex minor planetary bodies that are of great scientific and economic interest. Prior to these recent results, we were dependent on information gained by examining meteorites that have fallen to earth and our telescopic and radar observations of these objects in space. The Japan Aerospace Exploration Agency's (JAXA) Hayabusa mission, launched in 2003, returned to earth in June, 2010 with the first samples from an extraterrestrial body since the Apollo missions. The most immediate impact of these samples was to confirm that the Hayabusa's samples of Asteroid Itokawa were similar in composition to LL Chondrites, a common stony meteorite found on earth, validating the more than 40,000 meteorite finds on earth as being representative samples of objects in space. The NASA Deep Impact mission provided a different body of information for Comet Tempel-1 that included close up photography and spectroscopic analysis of a plume created by a designed impact into Comet Tempel-1. The NASA Dawn mission, launched in 2007, is now returning exceptional high resolution imagery of asteroid Vesta from the Main Asteroid Belt, and will proceed to the minor planet Ceres, arriving July, 2015.

This unprecedented body of data on the physical and chemical composition of asteroids and comets is as significant as the return of lunar samples by the Apollo program. The thermal and chemical evolution reflected in the initial results of the Hayabusa's samples of the Itokawa Asteroid indicated a complex thermal, radiation and impact history. These data provide hints on the early history of the solar system, the dynamic evolution of asteroids and the internal structure and composition of comets. These minor planetary bodies have much to contribute to our knowledge of the solar system and should not be neglected in the planning of future missions.

Close Encounters with Asteroids and Comets; New Insights from Dawn to Galileo

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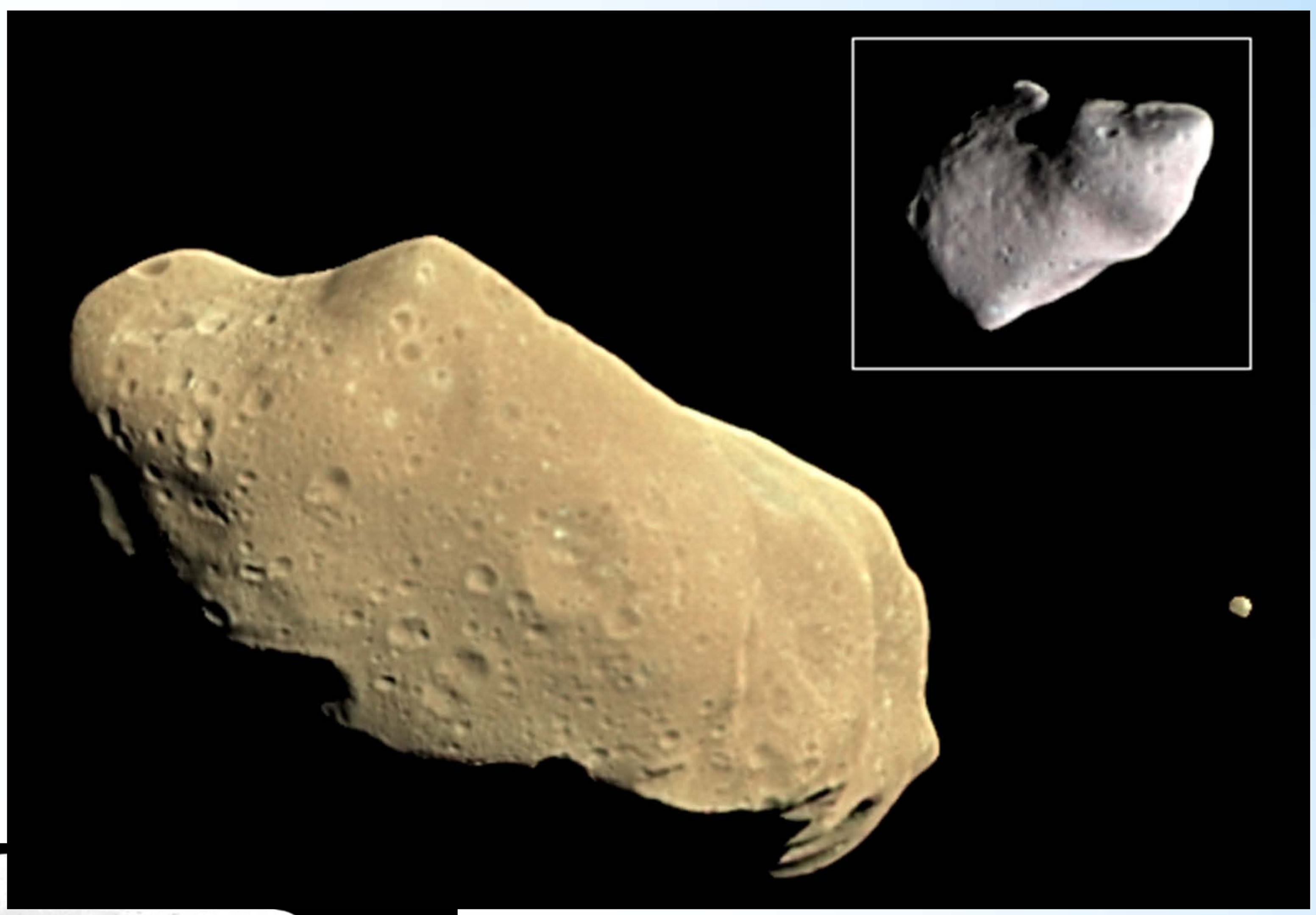
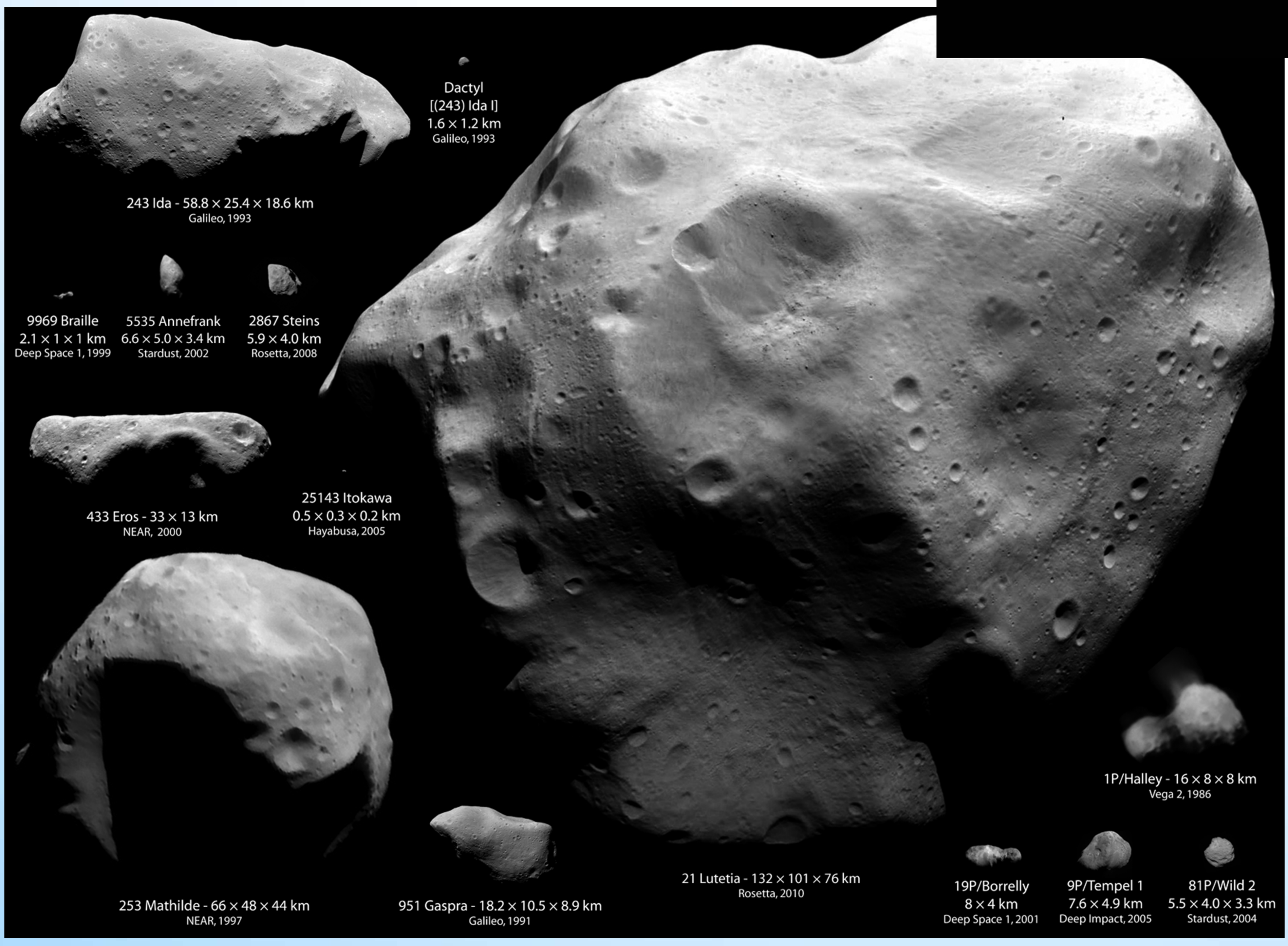
ABSTRACT: The recent visits, impacts, sampling and close-up photography of asteroids and comets have revealed complex minor planetary bodies that are of great scientific and economic interest. Prior to these recent results, we struggled to extend our knowledge of asteroids and comets from information gained by examining meteorites that have fallen to earth and our telescopic and radar observations of these objects in space. The Japan Aerospace Exploration Agency's (JAXA) Hayabusa-Minerva mission, launched in 2003, returned to earth in June, 2010 with the first samples from an extraterrestrial body since the Apollo missions. The most immediate impact of these samples was to confirm that the Hayabusa's samples of Asteroid Itokawa were similar in composition to LL Chondrites, a common stony meteorite found on earth, validating the more than 40,000 meteorite finds on earth as being representative samples of objects in space. The NASA Deep Impact-EPOXI missions provide a different body of information for Comet Tempel-1 and Comet Hartley-2 that include close up photography and spectroscopic analysis of the plume created by a designed impact into Comet Tempel-1. The NASA Dawn mission, launched in 2007, is now returning exceptionally high resolution imagery of asteroid Vesta from the Main Asteroid Belt, and will proceed to the minor planet Ceres, and will return similar data on Ceres beginning July, 2015.

The thermal and chemical evolution reflected in the initial results of the Hayabusa's samples of the Itokawa Asteroid indicated a complex thermal, radiation and impact history. As important as the initial lunar samples of the moon were, and are, to our understanding of the history of the solar system, the new samples from the asteroids and comets are as important. These minor planetary bodies have much to contribute to our knowledge of the solar system and should not be neglected in the planning of future missions.

The Near Earth Asteroids (NEAs) and some dormant comets in similar orbits have been proposed as the next logical stepping stones in the United States' space program on the way to Mars. Is a manned mission to an NEA justified? Because of their low gravity, a manned mission to an NEA can be conducted with less velocity change than a round trip mission to the moon or to Mars. An NEA sampling mission will, however, require a substantially longer amount of time than a Lunar mission, and the most favorable launch windows are considerably more restricted than Lunar missions.

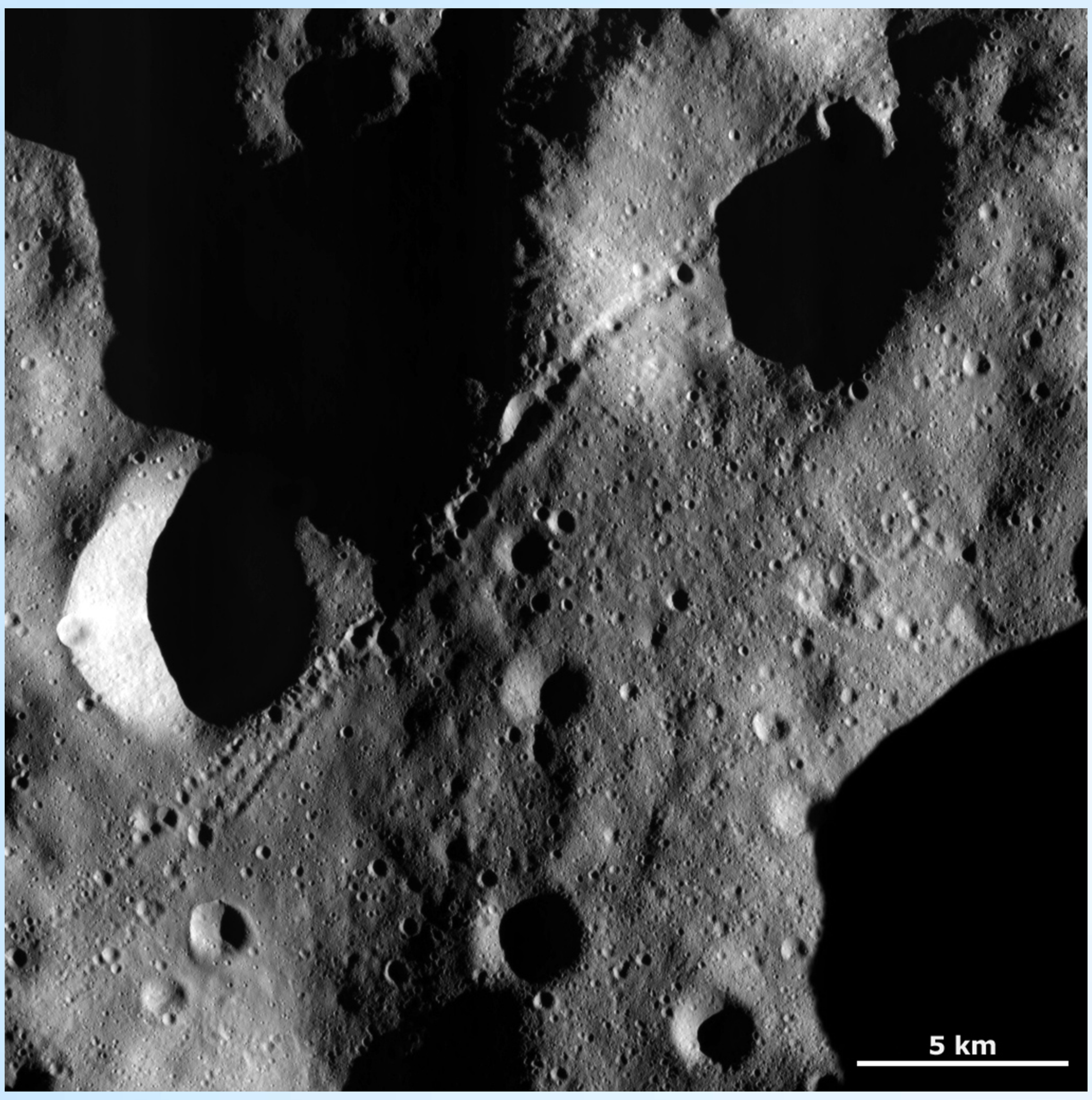
Why are we interested in Asteroids and Coments? Comets represent a reservoir of primordial material from the early formation of the solar system, and as such, provide a thermal, isotope, and chemical history of this period. Comets evolve as well, and it is proposed that as many as 12 percent of the dark asteroids may be extinct or dormant comets.





Asteroids: Asteroids fall into 3 basic types, C-Type, or carbonaceous chondrites, composed predominantly of unaltered volatiles, organics and ices; S-Type or stony asteroids composed predominantly of rocky material and M-Type or metallic. The M-type asteroids may be as much as 95 percent elemental metals composed of Iron, Nickel, Cobalt, Platinum group and REE. One, 1 km diameter M-Type Asteroid may contain 6 trillion US dollars of recoverable metals.

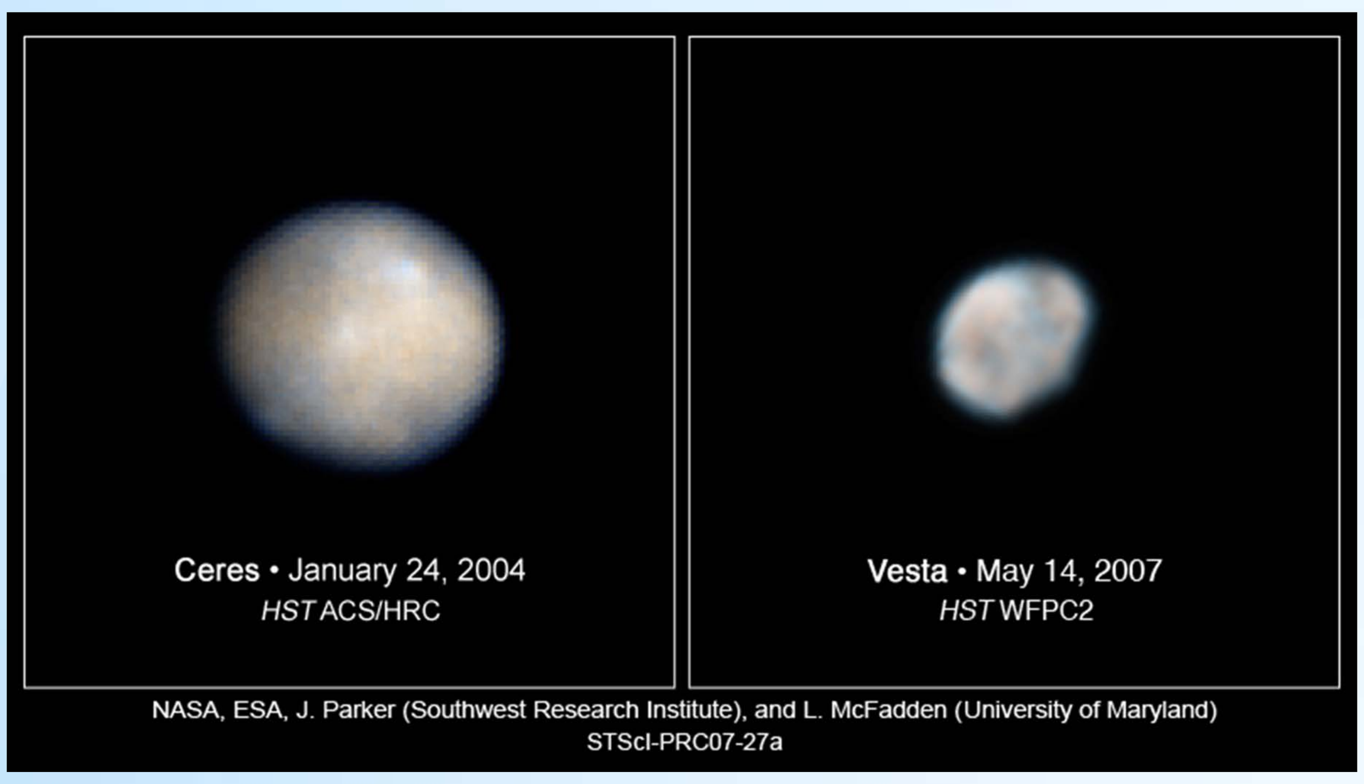
The DAWN Mission
Launched September 27th, 2007. Presently orbiting VESTA, the third largest asteroid in the Main Belt.



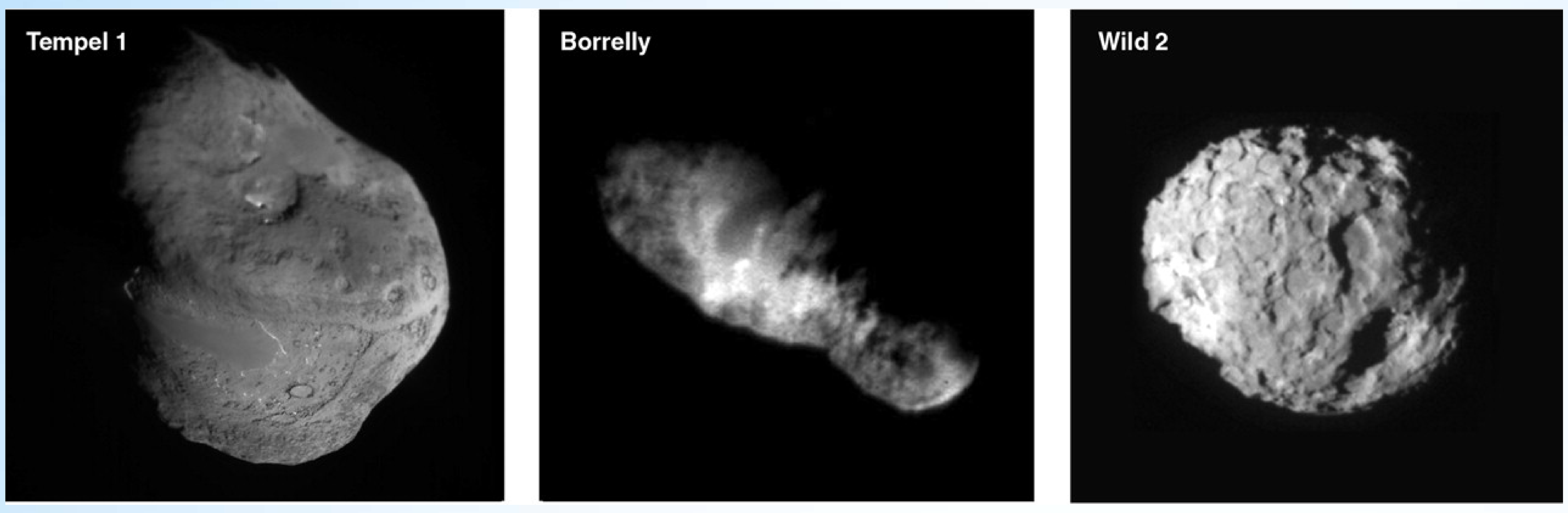
The DAWN Mission; Launched January 12, 2007. Currently orbiting the Asteroid Vesta, soon to depart for the minor planet, Ceres.

From JPL-NASA' DAWN Mission Web Page: (http://dawn.jpl.nasa.gov/mission/background.asp) Vesta, the brightest asteroid, is named for the ancient Roman goddess of the hearth and is the only asteroid ever visible with the naked eye. Found on March 29, 1807, by Heinrich Olbers, it was the fourth minor planet to be discovered. It is the second most massive and the third largest asteroid. It revolves around the Sun in 3.6 terrestrial years and has an average diameter of about 520 km(320 miles). Its surface composition is basaltic.

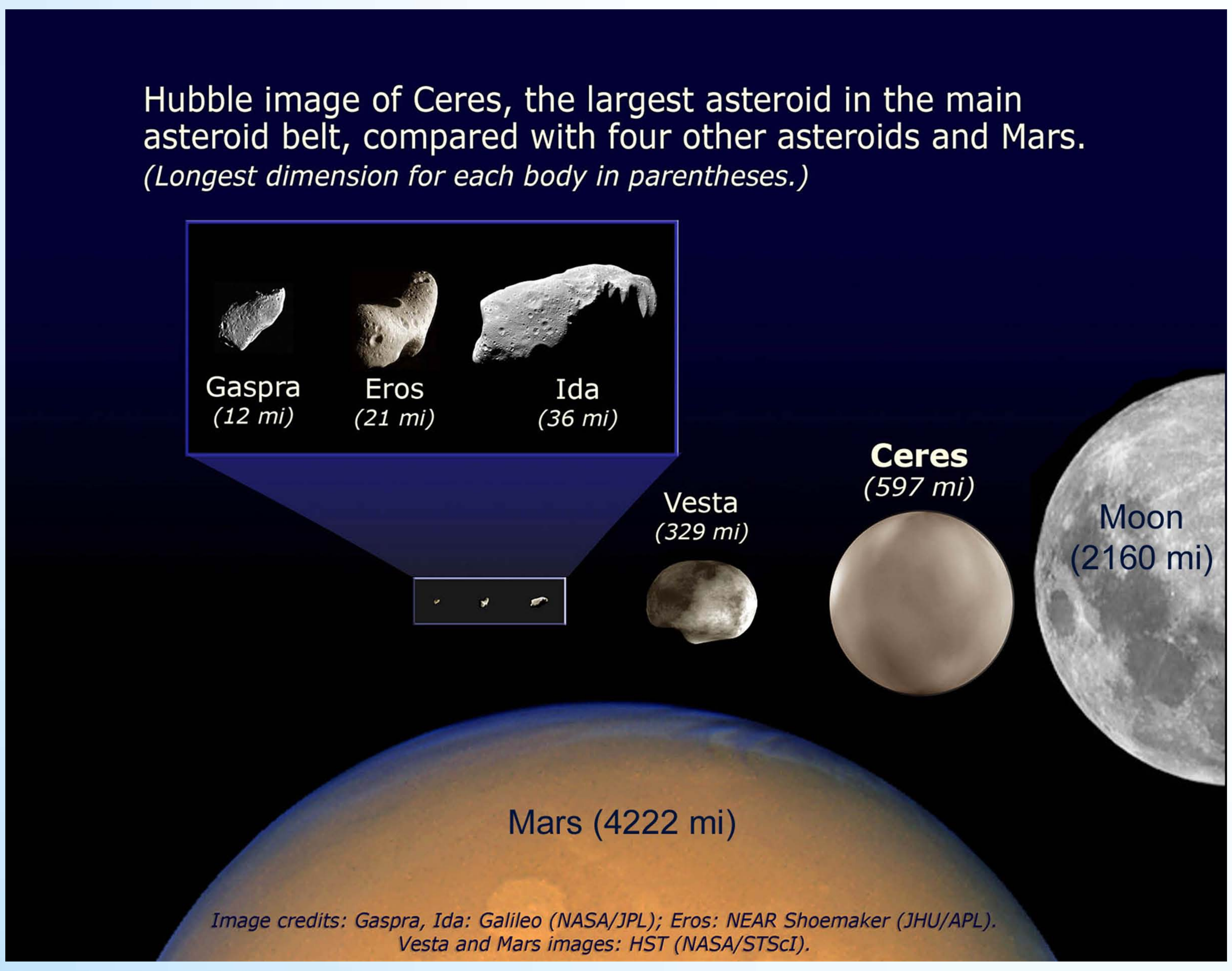
April 11, 2012 image from Dawn Mission framing Camera of chain of craters on Vesta. (JPL-NASA DAWN Project Team, 2012) Contrast this with the images shown below taken by the Hubble Space Telescope.



The exceptional detail and depth provided by the DAWN imaging have opened the way for detailed analyses of the surface conditions, and have provided the ability, should we chose, to identify and select interesting locations for robotic or manned missions for exploration and sampling.



Cometary nuclei visited in the last decades: Tempel 1 (left, NASA Deep Impact Team and University of Maryland) Borrelly, (NASA JPL) and Wild 2 (right; NASA, JPL and Stardust Team)



		Target	Results
OSIRIS-Rex (Proposed)	2016	Asteroid 1999 RQ36	Pending
Dawn	9-27- 07	Vesta and Ceres	Currently at Vesta
WISE (Wide Field Infrared Survey Explorer)	12-14- 09	Wide-field Infrared Survey, Comet Hartley 2	Detailed Photos of Comet Hartley 2
Deep Impact-EPOXI	1-12-05	Comet Tempel 1, Comet Hartley 2	Observed impacted ejected material from Tempel 1
Rosetta (ESA)	3-2-04	Comet 67P/Churyumov-Gerasimenko, Asteroid Steins, Asteroid Lutetia	Close-up images of Asteroids Steins and Lutetia in 2008 and 2010, respectively
Hayabusa-Minerva (Japan Space Agency)	5-9-03	Asteroid Itokawa	Asteroid sample return to Earth
Stardust-NExT	2-7-99	Asteroid Annefrank, Comet Wild 2, Comet Tempel-1 flyby	Detailed photos of two comets and returned comet sample to Earth for analysis
Deep Space 1	10-24-98	Asteroid 9969 Braille and Comet Borrelly	Test Platform for ion engine, found similarities between Braille and Vesta
Cassini	10-15-97	Saturn, Asteroid 2685 Masursky	Close photography of asteroid
NEAR Shoemaker	2-17-96	Asteroid Mathilde, Asteroid Eros	Rendezvous with EROS, controlled descent to asteroid surface, detailed surface mapping
Clementine	2-19-94	Moon, NEO Asteroid 1620 Geographos	First indication of ice on Lunar Poles
Galileo	10-18-89	Asteroid 951 Gaspra, Asteroid Ida	Discovered Ida orbited by Dactyl
Suisei (JSA)	8-18-85	Comet Halley	Flyby of Comet Halley
Sakigake (JSA)	1-7-85	Comet Halley	Flyby of Comet Halley
Giotto (ESA)	7-2-85	Comet Halley Comet Grigg-Skjellerup	Close flyby of 2 comets
International Cometary Explorer	8-12-78	Comet Giacobini-Zinner L1 LaGrange Point	Entered stable orbit at L1

The Deep Impact-EPOXI Mission

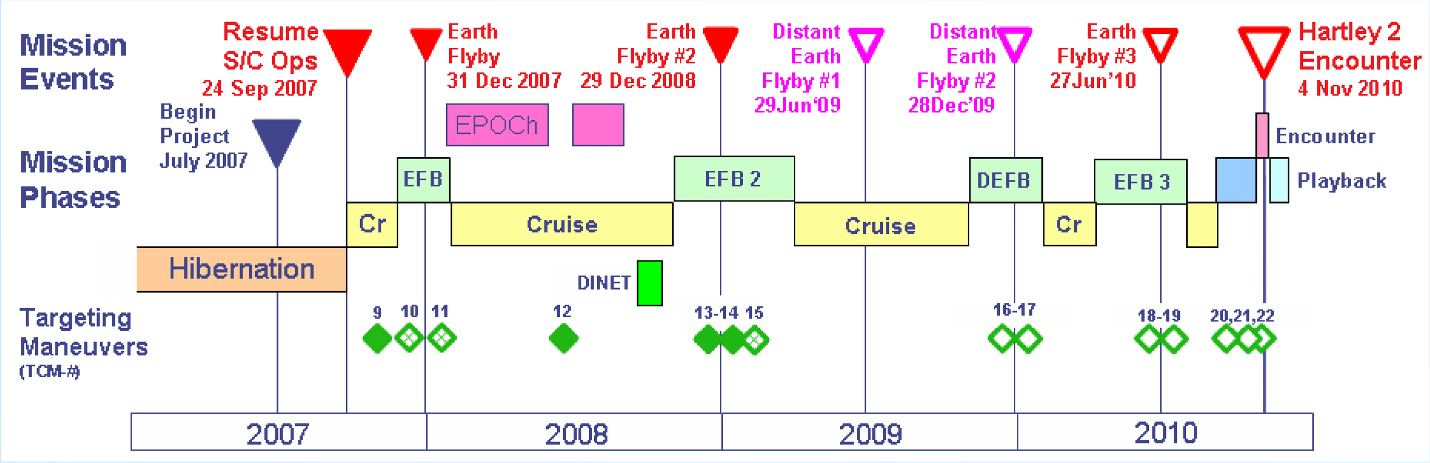
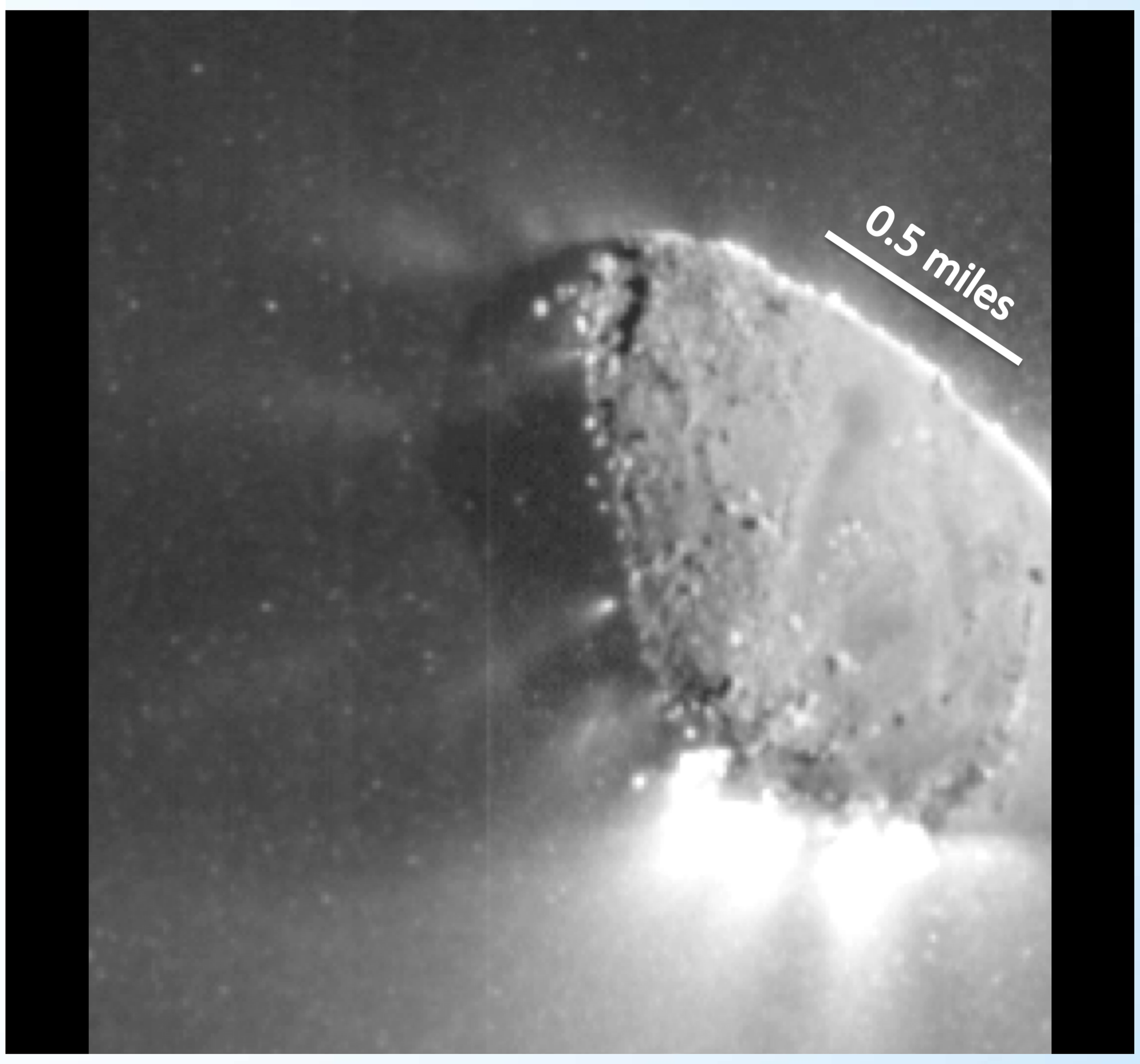
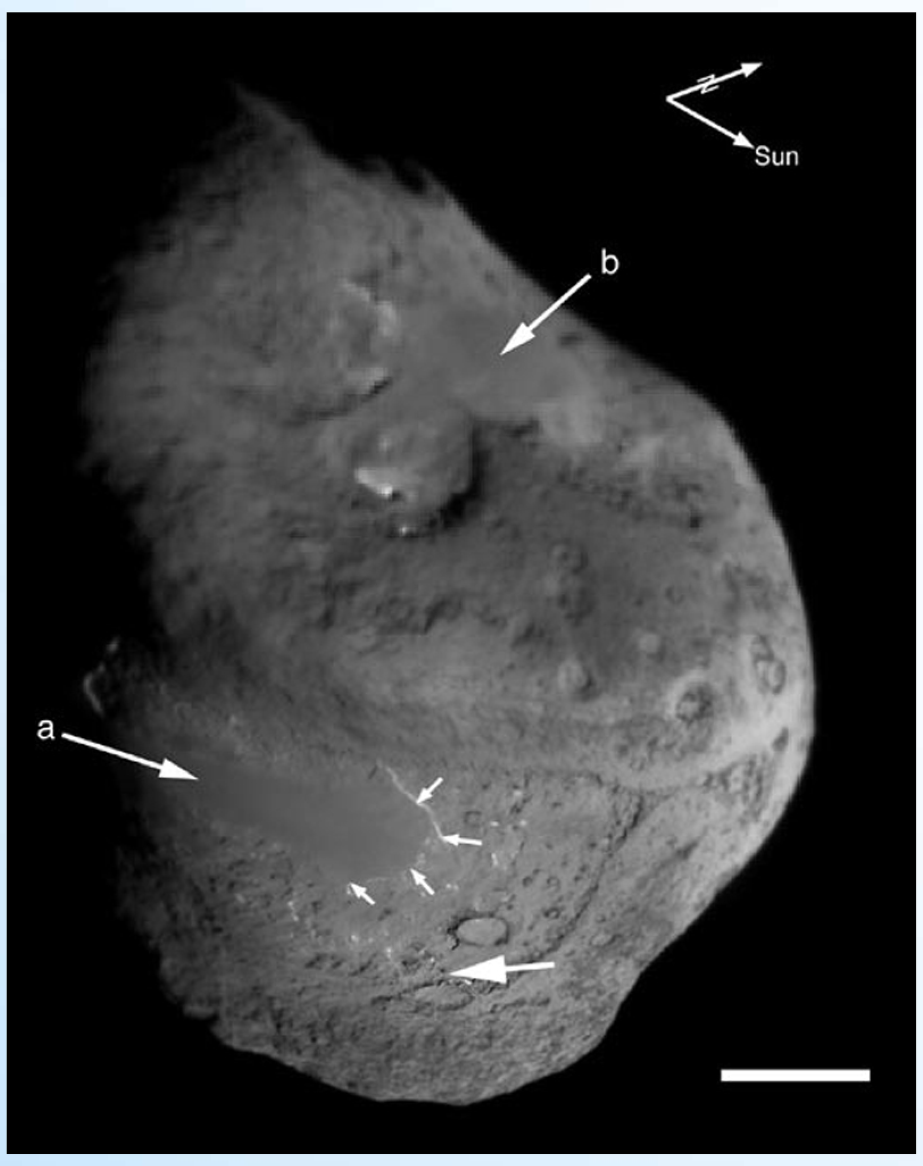


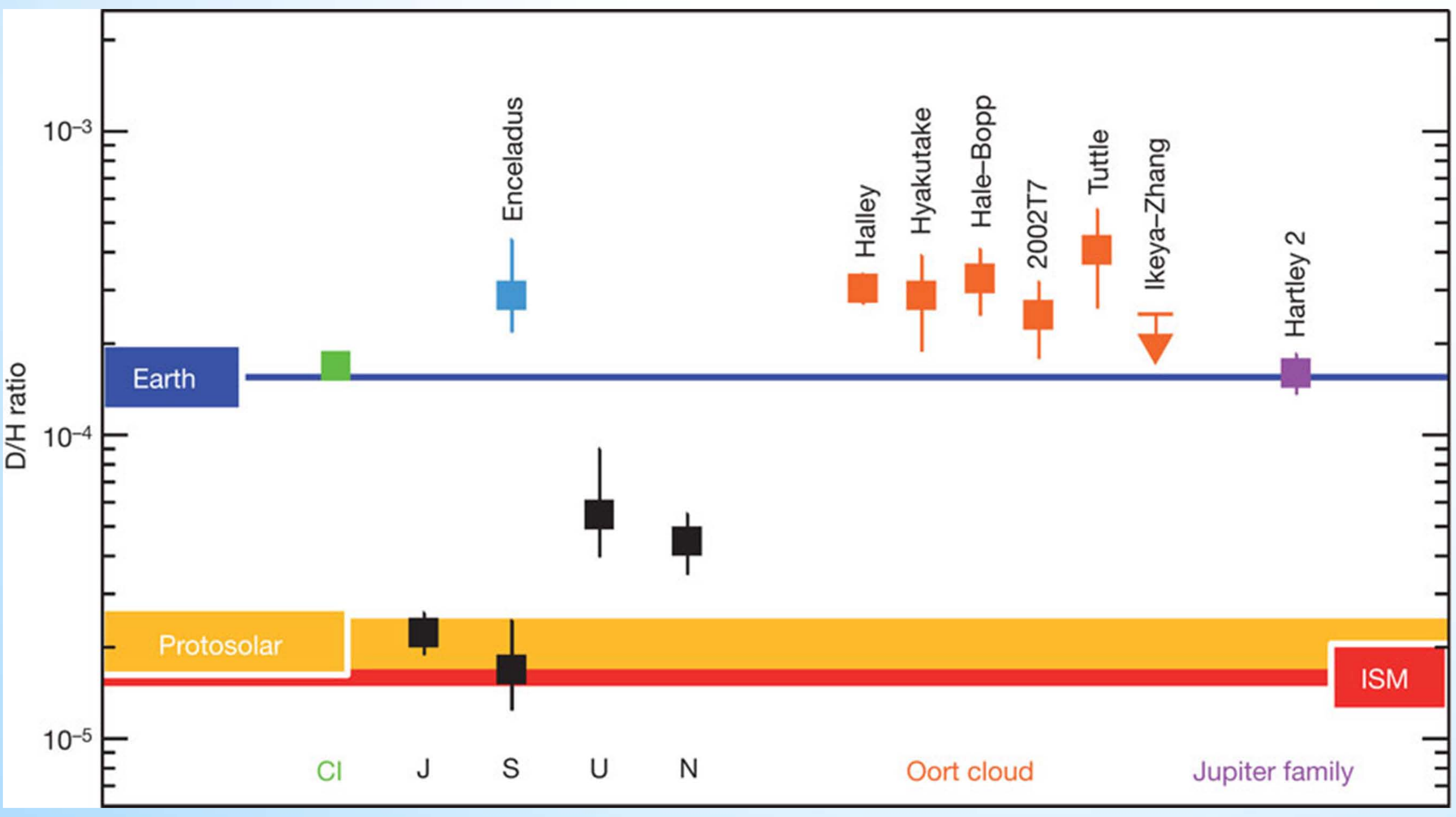
FIGURE 1.3 The nucleus of comet Tempel 1 at the moment it was struck by the impactor from the Deep Impact spacecraft on July 4, 2005. This was a Discovery mission. SOURCE: NASA/JPL-Caltech/University of Maryland.

The “Deep Impact-EPOXI” mission provided an opportunity for both close inspection of the surface of a comet and an analysis of the composition of a comet’s regolith by volatilizing a portion of the surface material. CN, C2, C3, OH, HCN and NH were all detected in the emission bands of the impact plume. (Nasa Photo from National Academies Press “Vision and Voyages for Planetary Sciences in the Decade 2013-2022.) Data from (A’Hearn, M. F., et. al., 2005)





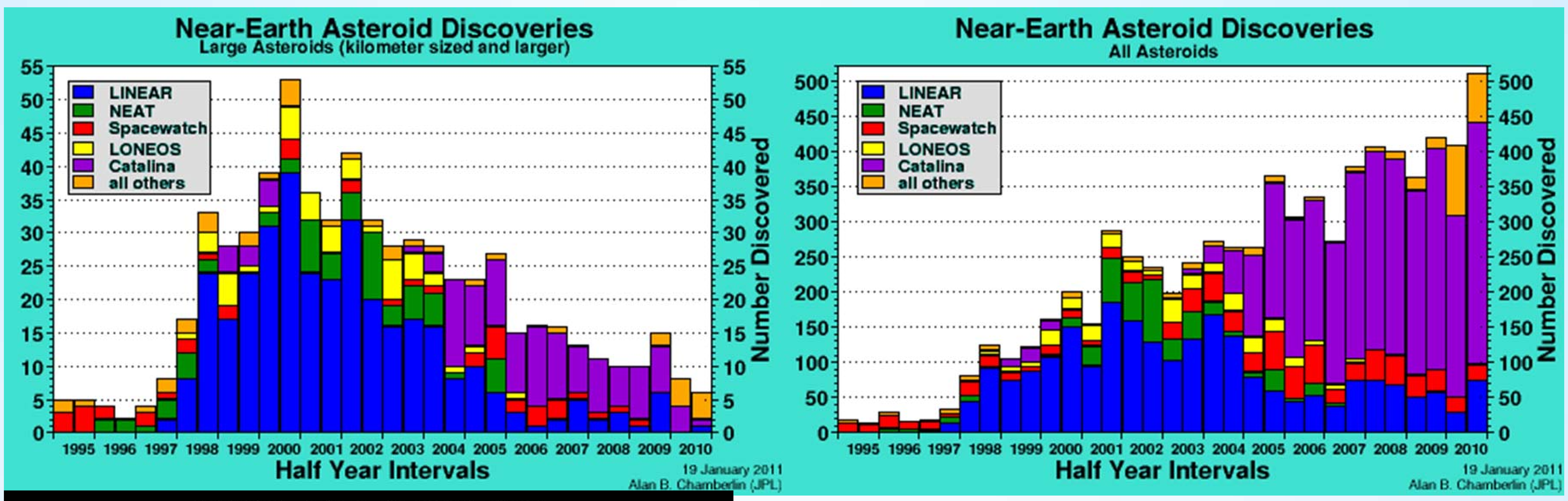
(photos available on line from NASA Images: http://www.nasa.gov/images/content/159837main_di_T1_Composite_Map_800.jpg) The impact site is indicated by the third large arrow. Small grouped arrows highlight a scarp (a cliff or steep slope along the edge of a plateau) that is bright due to illumination angle. They show a smooth area to be elevated above the extremely rough terrain. The white scale bar in the lower right represents 1 km across the surface of the comet nucleus. The two directional arrows (vectors) in the upper right point to the Sun and Celestial North. Photo Credit: NASA/UM M. F. A'Hearn et al., Science 310, 258 (2005); published online 8 September 2005 (10.1126/science.1118923).

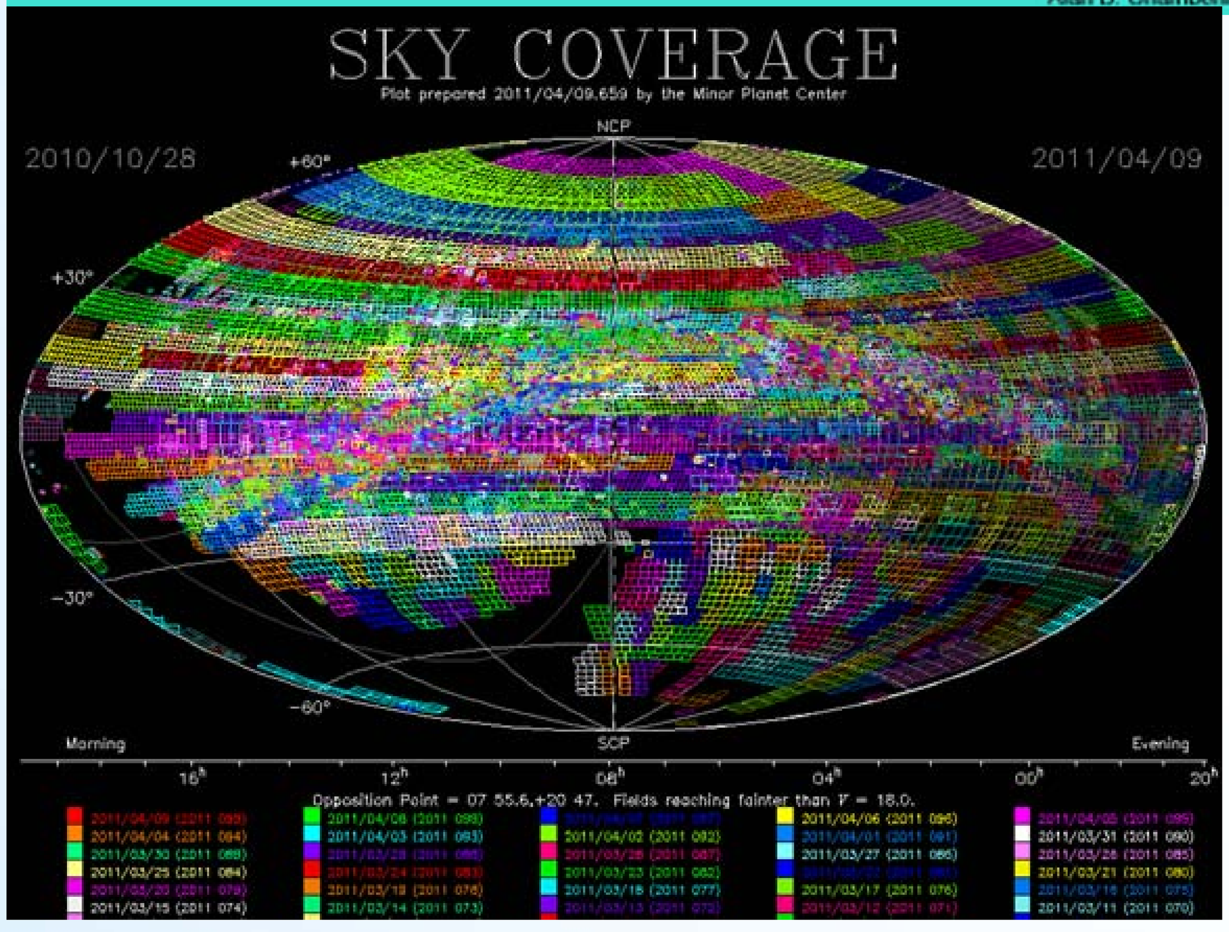


After Hartogh, P., et. al., 2011. The D/H ratio in the Jupiter-family comet 103P/Hartley 2 is the same as the Earth’s ocean value and the chondritic CI value. Uranus and Neptune have been enriched in deuterium by the mixing of their atmospheres with D-rich protoplanetary ices.

Why are these missions important?

- **Why are we interested in the Near Earth Asteroids and Comets?**
  - **<u>Logistical Issues.</u> The Near Earth Asteroids represent the easiest local sources of in-space rocket fuels, volatiles and oxygen to support extraterrestrial space missions**
  - **<u>Economic.</u> The NEAs contain essentially an unlimited supply of strategic materials, platinum group metals and cobalt, nickel and iron for building materials.**
  - **<u>Science.</u> The asteroids and comets provide unique windows on the characteristics of the early solar system, and a platform for monitoring near sun conditions, and outer planet environments.**
  - **<u>Self Preservation.</u> Earth crossing asteroids and comets greater than 50 meters in diameter represent potentially catastrophic events that threaten Earth's environment. Detection, monitoring and intervention can only occur if we are aware of the impending impact.**





NEO Discovery Statistics
as of January 19th, 2010

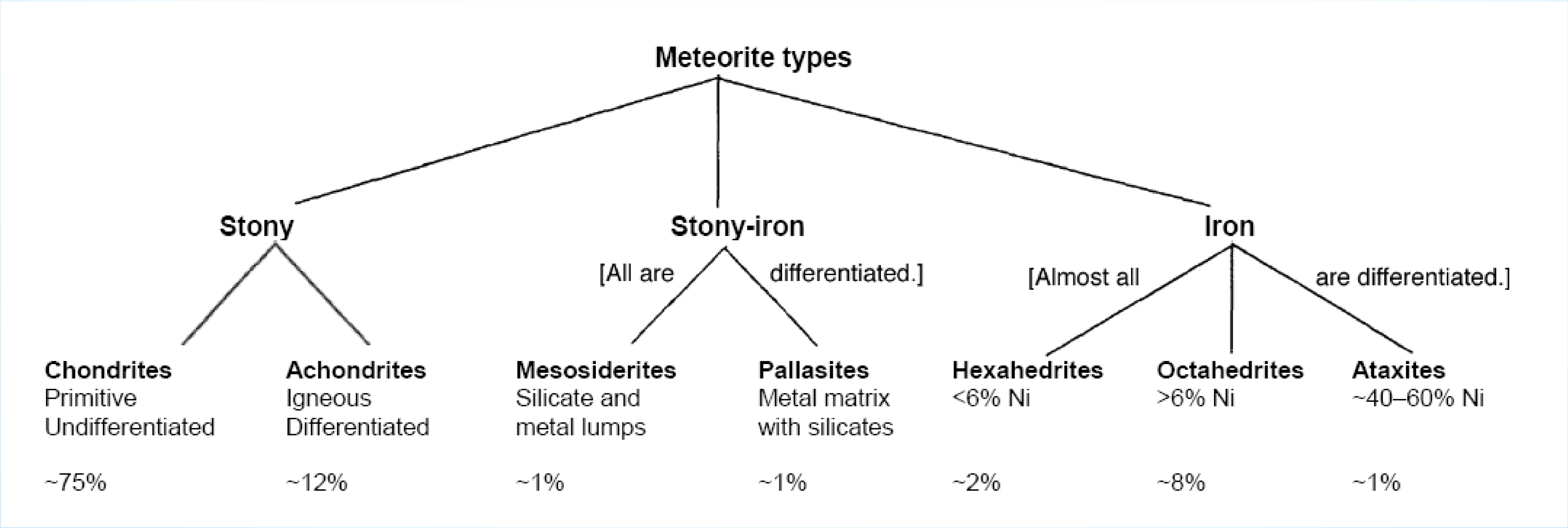
- 87 Comets
- 7,970 total number discovered
- 824 Larger than 1 KM
- 1,217 with orbits that pass within 0.05 AUs of Earth (PHA)
- 148 PHAs larger than 1 km

Figure 5. Mineralogical, Chemical and Physical Properties of Asteroids

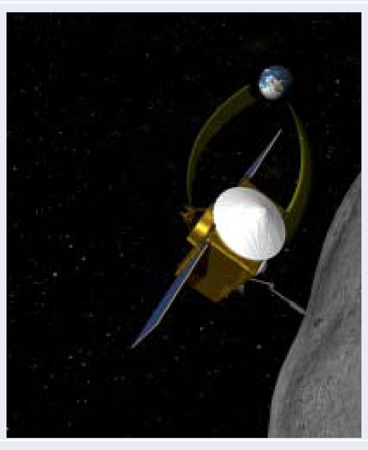
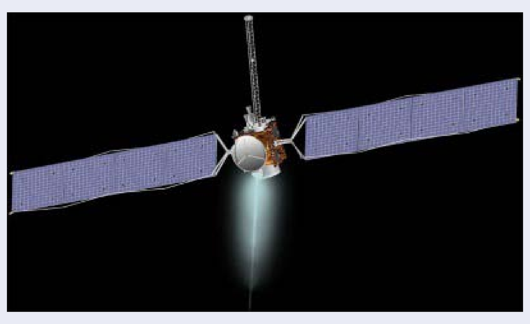
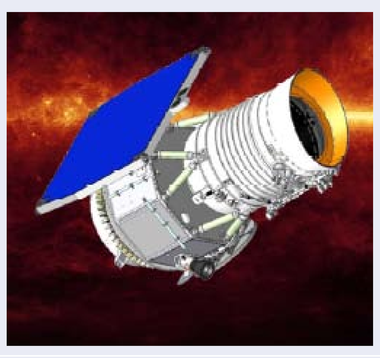
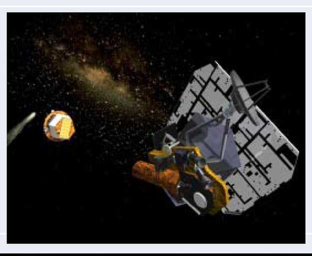
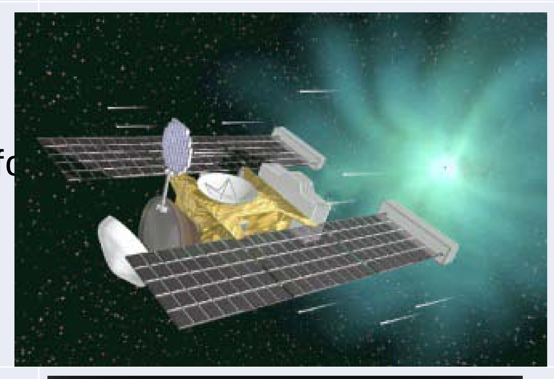
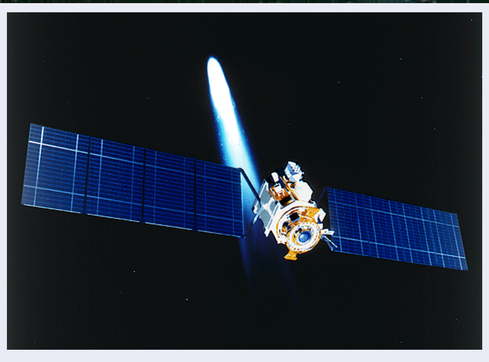
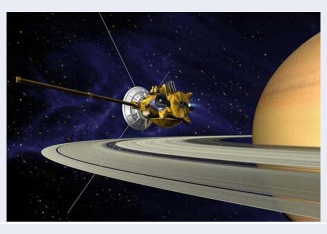
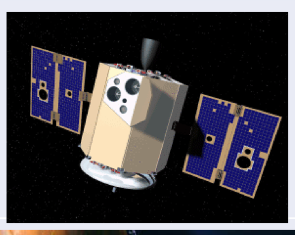
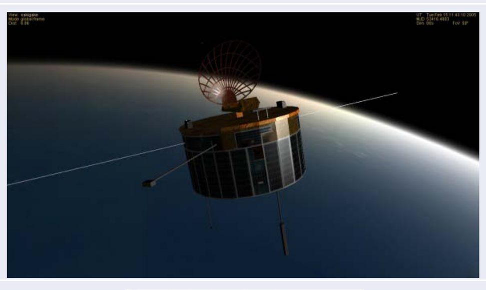
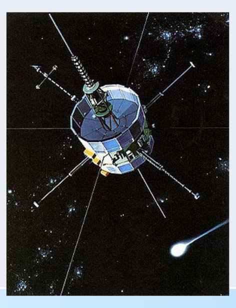
	Mineral	C2-Type	C1-Type	S-Type	M-Type	Lunar Regolith
Free Metals	Fe	10.7%	0.1%	6-19%	88%	0.1%
	Ni	1.4%	—	1-2%	10%	—
	Co	0.11%	—	0.1%	0.5%	—
Volatiles	C	1.4%	1.9-3.0%	3%	—	0.014%
	H2O	5.7%	12%	0.15%	—	0.045%6
	S	1.3%	2%	1.5%	—	0.12%
Mineral Oxides	FeO	15.4%	22%	10%	—	15.8%
	SiO2	33.8%	28%	38%	—	42.5%
	MgO	23.8%	20%	24%	—	8.2%
	Al2O3	2.4%	2.1%	2.1%	—	13.8%
	Na2O	0.55%	0.3%	0.9%	—	0.44%
	K2O	0.04%	0.04%	0.1%	—	0.15%
	P2O5	0.28%	0.23%	0.28%	—	0.12%
	CaO	—	—	—	—	12.1%
	TiO2	—	—	—	—	7.7%
Physical	Density (g/cm^3)	3.3	2.0-2.8	3.5-3.8	7.0-7.8	1.5-1.9

Concentrations and Potential Value of Rare Earth Elements, Precious Metals and Platinum Group Metals in "Typical" 1 km Diameter Asteroids Derived from Chemical Composition of Meteorite Finds on Earth

	concentration ppm	price $/kg	source	mass @ 3.3	$
Semiconductors					
Phosphorous (P)	1300	$0.06	USGS 2009	2.25E+06	1.24E+08
Gallium (Ga)	60	$480.00	USGS 2009	1.04E+05	4.98E+10
Germanium (Ge)	210	$950.00	USGS 2009	3.63E+05	3.45E+11
Arsenic (As)	3.7	$2.02	USGS 2009	6.39E+03	1.29E+07
Selenium (Se)	36	$50.60	USGS 2009	6.22E+04	3.15E+09
Indium (in)	0.46	$500.00	USGS 2009	7.95E+02	3.97E+08
Antimony (Sb)	0.047	$5.06	USGS 2009	8.12E+01	4.11E+05
Tellurium (Te)	0.45	$145.00	USGS 2009	7.78E+02	1.13E+08
Platinum & Precious Metals					
Ruthenium (Ru)	13	$6,515.99	USGS 2009	2.25E+04	1.46E+11
Rhodium (Rh)	4.8	$79,751.86	USGS 2009	8.29E+03	6.61E+11
Palladium (Pd)	1.3	$24,595.32	USGS 2009	2.25E+03	5.52E+10
Silver (Ag)	0.46	$954.88	WSJ	7.95E+02	7.59E+08
Rhenium (Re)	3.7	$3,100.00	USGS 2009	6.39E+03	1.98E+10
Osmium (Os)	9	$14,467.84	USGS 2009	1.56E+04	2.25E+11
Iridium (Ir)	33	$19,871.73	USGS 2009	5.70E+04	1.13E+12
Platinum (Pt)	35	$55,022.79	USGS 2009	6.05E+04	3.33E+12
Gold (Au)	0.5	$45,076.31	WSJ	8.64E+02	3.89E+10
Other Important Metals					
Copper	100	$9.24	WSJ	1.73E+05	1.60E+09
Cobalt (Co)	0.25	$39.60	USGS 2009	4.32E+06	1.71E+11
Titanium (Ti)	14.00%	$0.56	USGS 2009	2.42E+06	1.35E+09
Chromium (Cr)	5.00%	$10.00	USGS 2009	8.64E+05	8.64E+09
Nickel (Ni)	6.00%	$14.91	USGS 2009	1.04E+06	1.55E+10
Molybdenum (Mo)	0.50%	$50.00	USGS 2009	8.64E+00	4.32E+05



Missions to Comets and Asteroids

Mission	Launch Date	Target	Results	
OSIRIS-REX (proposed)	7/8/2016	Asteroid 1999 RQ36	The mission, called Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer, or OSIRIS-REx, will be the first U.S. mission to carry samples from an asteroid back to Earth.	
DAWN	9/27/2007	Vesta and Ceres	Dawn is a mission designed to rendezvous and orbit the asteroids 4 Vesta and 1 Ceres. The scientific objectives of the mission are to characterize the asteroids' internal structure, density, shape, size, composition and mass and to return data on surface morphology, cratering, and magnetism. Currently at Vesta.	
WISE	12/14/2009	Comet Hartley 2	Wide Field Infrared Survey Explorer.WISE, will scan the entire sky in infrared light, picking up the glow of hundreds of millions of objects and producing millions of images.	
Deep Impact-EPOXI	1/12/2005	Comet Tempel 1, Comet Hartley 2	Observed impact ejecta material from Tempel 1	
Rosetta (ESA)	3/2/2004	Comet 67P/Churyumov-Gerasimenko, Asteroids Steins, Lutetia	Close-up images of Asteroids Steins and Lutetia in 2008 and 2010, respectively	
Hayabusa-Minerva (Japan Space Agency)	5/9/2003	Asteroid Itokawa	Asteroid Sample Return Mission to Earth	
Stardust-NExT	2/7/1999	Asteroid Annefrank, Comet Wild 2, Comet Tempel-1 flyby	Detailed photos of two comets and returned comet sample to Earth fo analysis	
Deep Space 1	10/24/1998	Asteroid 9969 Braille and CometBorrelly	Test Platform for Ion Engine, found similarities between Braille and Vesta	
Cassini	10/15/1997	Saturn, Asteroid 2685 Masursky	Close photography of Asteroid Masursky while on way to primary mission at Saturn	
Near Shoemaker	2/17/1996	Asteroid Mathilde, Asteroid Eros	Rendezvous with EROS, controlled descent to surface, detailed surface mapping.	
Clementine	2/19/1994	Moon, NEO Asteroid 1620 Geographos	First indication of ice on Lunar Poles	
Galileo	10/18/1989	Jupiter, Asteroid 951 Gaspra, Asteroid Ida	Discovered Ida Orbited by Dactyl	
Suisei (JSA)	8/18/1985	Comet Halley	Flyby of Comet Halley	
Sakigake (JSA)	1/7/1985	Comet Halley	Flyby of Comet Halley	
Giotto (ESA)	7/2/1985	Comet Halley, Comet Grigg-Skjellerup	Close flyby of two comets	
International Cometary Explorer	8/12/1978	Comet Giacobini-Ziner, L1 LaGrange Point	Entered Stable orbit at L1	

Arguments for Missions to Asteroids and Near Earth Objects:

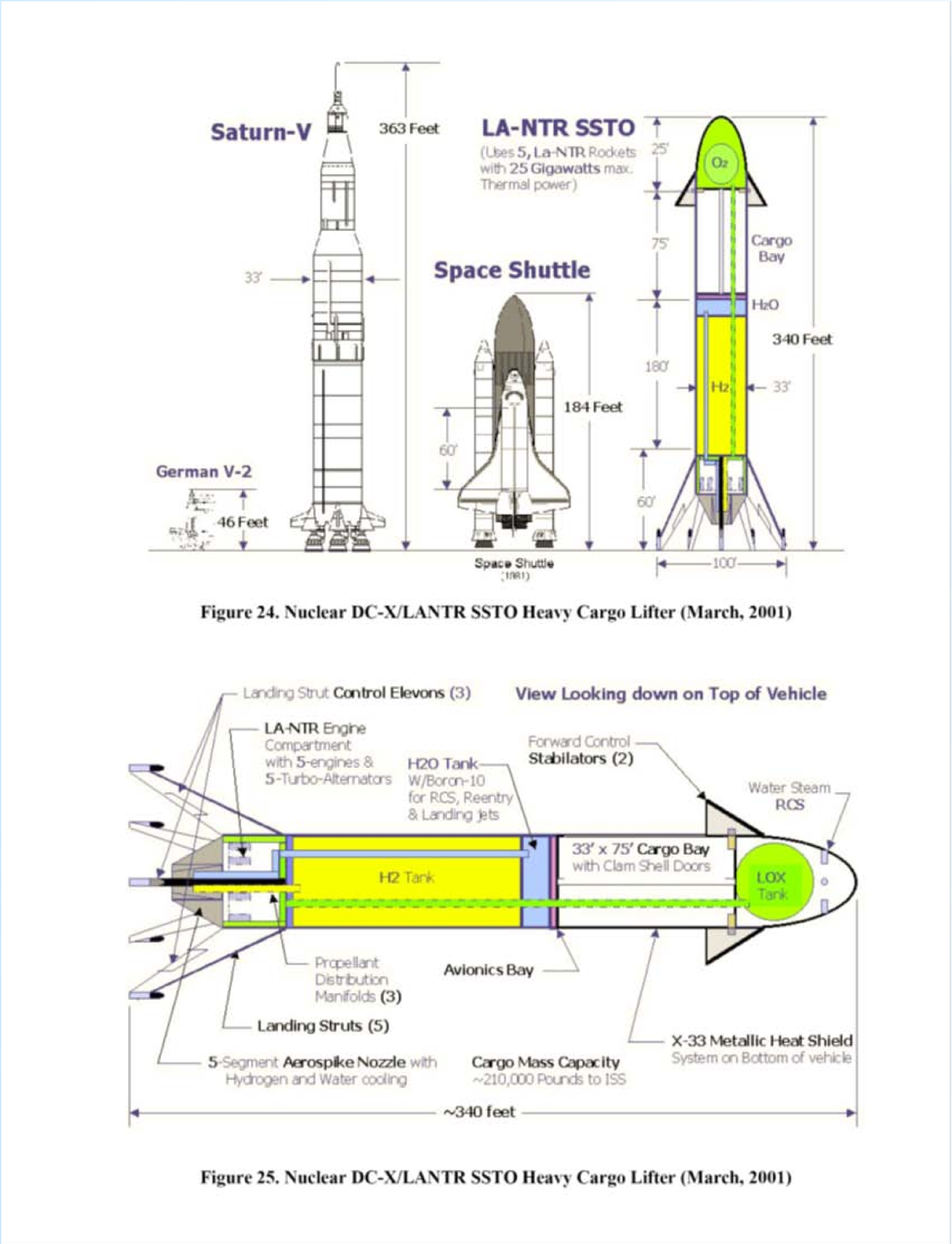
➢Mass in orbit is worth 10 to 15 times equivalent Mass on the ground.

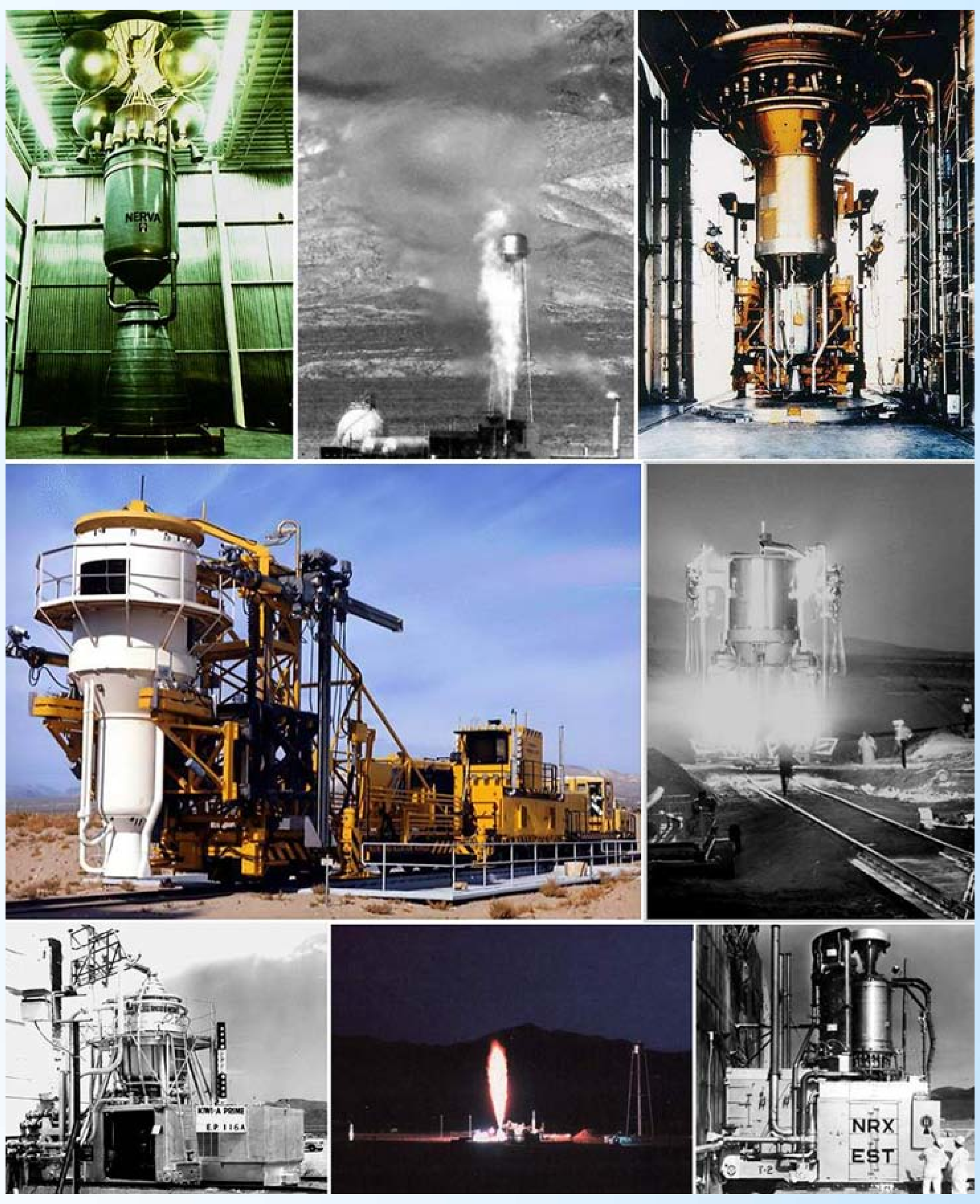
➢If launch cost is $15-20,000 per Kilogram, then every kilogram in orbit is as valuable as 17 kilograms of Silver, a kilogram of Osmium or Iridium, 1/3 a kilogram of Gold or 1/5 a kilogram of Platinum.

➢ From the perspective of being in space, a metric ton of water in space has a value of $15 Million Dollars. …….A one kilometer diameter C-type asteroid or dormant comet composed of 30 percent water, contains 150 million metric tons of water. If this had to be launched from Earth's surface it would cost 2,250 trillion dollars, which is obviously impractical.

➢The conclusion is we must use in situ materials found in space, to effective explore and exploit space resources.

So, how do we get to space?
We must use high energy density propulsion systems, and that means nuclear power.
<u>ALL</u> of the research and design work has really been completed, all we need is the political will, and public support.





"…NASA's recent space nuclear power and propulsion program initiative will hopefully re-energize nuclear propulsion R&D in a very serious way. <u>**Nuclear DC-X has such far-reaching capabilities that it represents a new and vital way of realizing the benefits of space. This advanced propulsion concept can be implemented within 5 years to meet all manned and unmanned space mission requirements.**</u>**" Ref: Advanced Propulsion Study, AIR FORCE RESEARCH LABORATORY, AIR FORCE MATERIEL COMMAND, EDWARDS AIR FORCE BASE CA 93524-7048. September 2004. Special Report AFRL-PR-ED-TR-2004-0024**

References:

1. Paul Hartogh, Dariusz C. Lis, Dominique Bockele´e-Morvan, Miguel de Val-Borro, Nicolas Biver, Michael Ku¨ppers, Martin Emprechtinger, Edwin A. Bergin, Jacques Crovisier, Miriam Rengel, Raphael Moreno, Slawomira Szutowicz & Geoffrey A. Blake. "Ocean-like water in the Jupiter-family comet 103P/Hartley 2". Nature Letter. 5 October 2011. V 478 Issue 7368. pgs. 218-220.
2. Biver, N. Bockelee-Morvan, D., Crovisier, J., Colom, P., Henry, F., Moreno, R., Paubert, G., Despois, D. and Lis, D. C., Chemical Composition Diversity Among 24 Comets Observed at Radio Wavelengths. Earth, Moon and Planets. Vol 90. pgs 323-333. 2002.
3. A'Hearn, M. F., M. J. S. Belton, W. A. Delamere, J. Kissel, K. P. Klaasen, L. A. McFadden, K. J. Meech, H. J. Melosh, P. H. Schultz, J. M. Sunshine, P. C. Thomas, J. Veverka, D. K. Yeomans, M. W. Baca, I. Busko, C. J. Crockett, S. M. Collins, M. Desnoyer, C. A. Eberhardy, C. M. Ernst, T. L. Farnham, L. Feaga, O. Groussin, D. Hampton, S. I. Ipatov, J.-Y. Li, D. Lindler, C. M. Lisse, N. Mastrodemos, W. M. Owen Jr., J. E. Richardson, D. D. Wellnitz1 and R. L. White. Deep Impact: Excavating Comet Tempel 1. Science V. 310 No. 5746. pgs. 258-264. October, 2005.
4. National Research Council. Vision and Voyages for Planetary Science in the Decade 2013-2022. 2012 National Academies Press ISBN 978-0-309-22464-2. 400 pgs.
5. Davis, E. W., Advanced Propulsion Study Special Report AFRL-PR-EDE-TR-2004-0024. 2004. Available online at: http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA426465

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