Energy Minerals in Near-Earth Asteroids*

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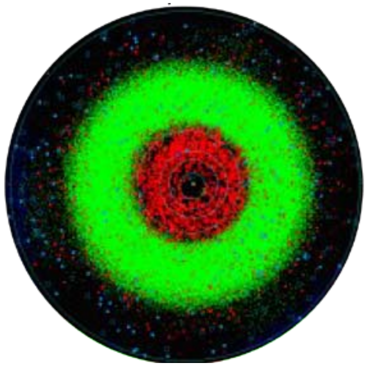
Abstract

Asteroids represent the most accessible, resource-rich bodies in the Solar System. Primary energy minerals in these bodies are organic molecules ranging from low-weight molecular hydrocarbons to high-molecular weight kerogen-like material. In well-characterized carbonaceous chondrites such as Murchison, ~25% of organic matter is present as solvent-soluble or free compounds, which include aliphatic and aromatic hydrocarbons. The remaining 75% is a complex solvent-insoluble macromolecular material. Methane is present at the 20-30 ppm level in Murchison. In contrast, methane is below current detection limits in the Orgueil CI chondrite, another carbon-rich meteorite. Successful extraction of this potential resource requires strong synergy between ground-based observations and engineering solutions.

Asteroids are diverse bodies with a wide range of properties. Several hundred thousand asteroids have been discovered. Asteroids are characterized based on their spectral properties, primarily in the visible and infrared wavelength regions. Of primary interest for resource extraction are D-type and C-type asteroids. D-type asteroids are low-albedo objects (0.02-0.06) and have relatively featureless spectra with steep red slopes. C-type asteroids also have low albedos (0.03-0.10) with slight bluish to slight reddish slopes and absorptions blueward of 0.5 µm. Both D- and C-types are designated as "primitive carbonaceous asteroids" and are likely composed of organic-rich compounds and hydrated minerals. The connection between organic-rich meteorites and "primitive carbonaceous asteroids" is tenuous and requires advanced exploration to identify the resources of near-Earth space.

Target selection for resource extraction is limited by our poor understanding of the asteroid population. Ground-based surveys of the asteroid population focus on detection and orbit determination. Orbit determination is only the first step in resource assessment. A real need exists for extension of Asteroid Surveys to include physical characterization. The most effective ground-based characterization is done using radio telescopes. Radar data provides the shape and size of asteroid, evidence of craters, boulders and surface features, evidence of regolith, size distribution of regolith, and the presence of satellites, which allow for a mass determination. Only with such data in hand can effective reconnaissance missions be planned to identify energy minerals in the inner Solar System.



Energy Minerals in Near-Earth Asteroids

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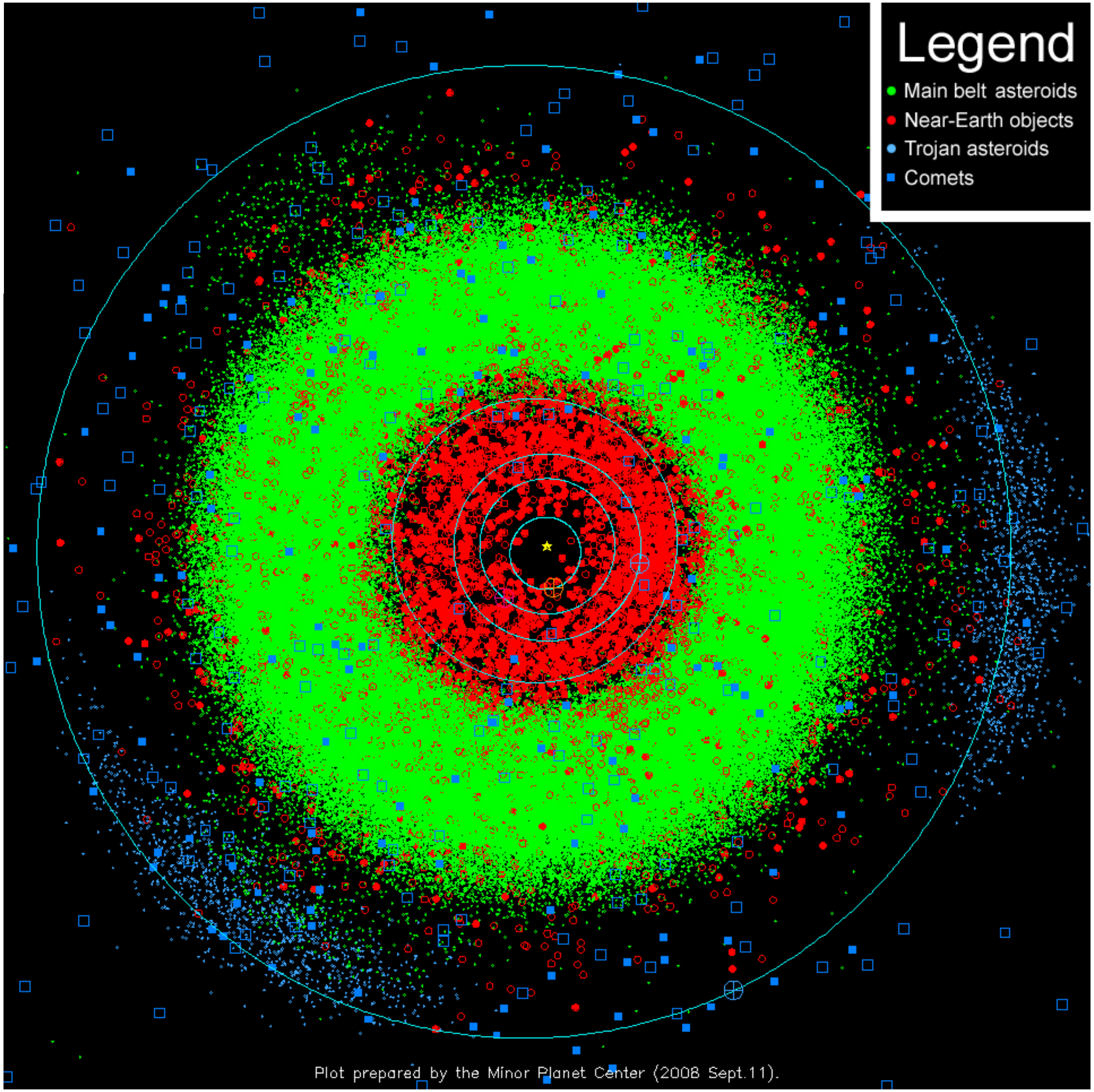
Asteroids Are Diverse Bodies With a Wide Range of Properties

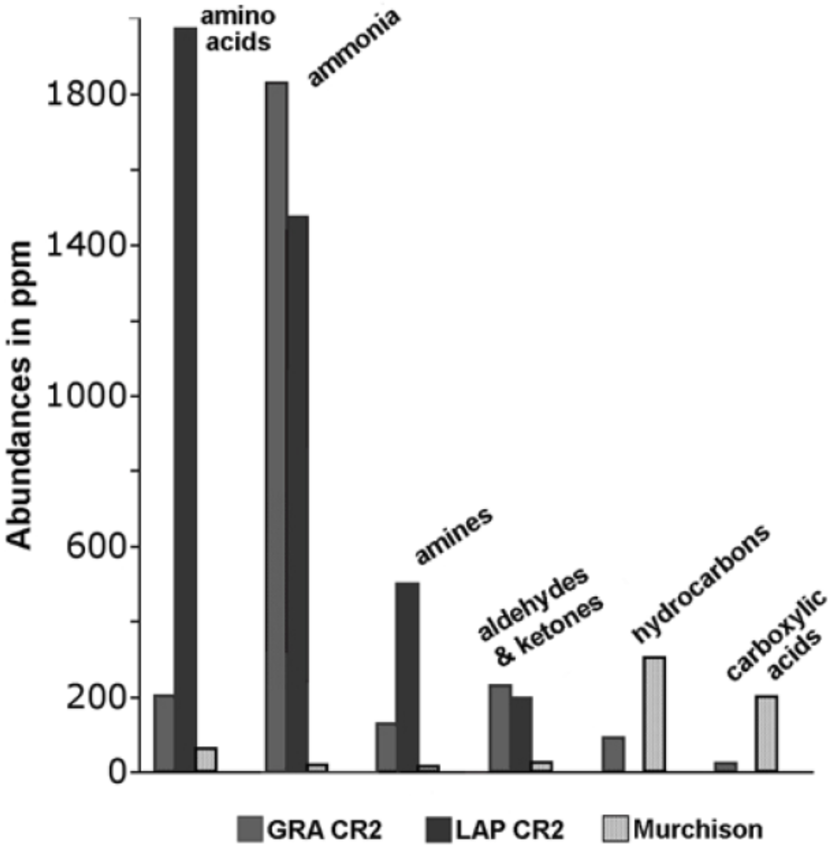
- Several hundred thousand asteroids have been discovered
- We know >99% of the asteroids larger than 100 km in diameter.
- We have cataloged ~1/2 of the asteroids in the 10-100 km range.
- There are more than a million asteroids in the 1-km range



Plot prepared by the Minor Planet Center (2008 Sept.11).

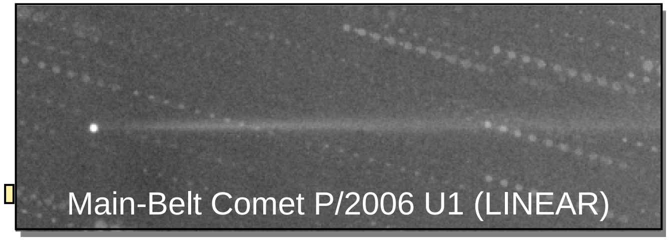
Energy Minerals in Asteroids are Typically Equated with Hydrocarbons

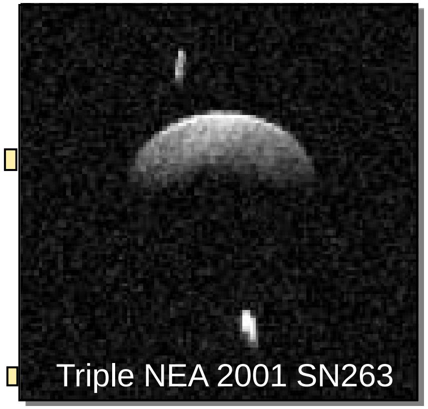
- The classic Murchison (CM) carbonaceous chondrite contains several hundred ppm hydrocarbons
- However, the organic chemistry of carbonaceous asteroids is diverse
- Recent work on the CR chondrites (Pizzarello et al. 2009) reveals a vastly different organic chemistry
- Don't expect all carbonaceous asteroids to look like Murchison



How to Find the Energy Minerals: The First Steps of Physical Characterization are Accomplished From the Ground

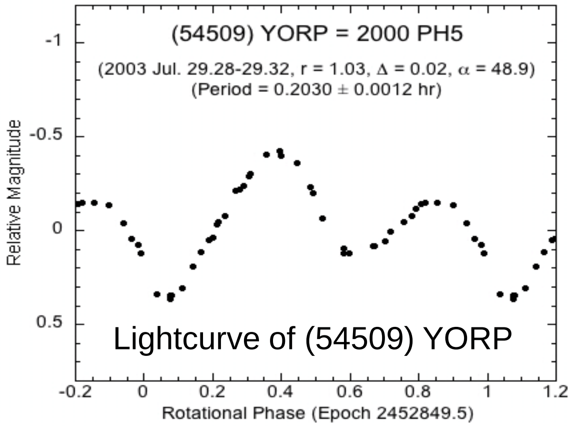
Visible	*Astrometry* - refine orbit and ephemerides *Cometary Activity* - evidence of volatiles *Satellites* - evidence of recent splitting / fresh surface material, mass determination
Radar	*Astrometry* - very high precision orbit refinement *Shape Model* - shape and size of asteroid *Surface Features* - evidence of craters, boulders and surface features down to ~7 meters *Surface Roughness* - evidence of regolith, size distribution of regolith *Satellites* - evidence of recent splitting / fresh surface material, mass determination
Meteors	*Detection* - evidence of past volatile outgassing *Orbits* - past history of volatile outgassing


Main-Belt Comet P/2006 U1 (LINEAR)

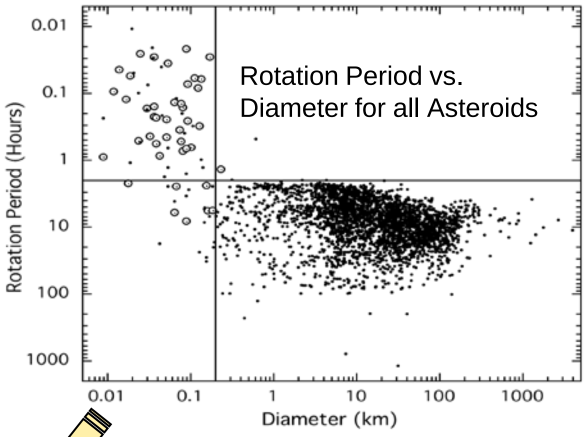

Triple NEA 2001 SN263


September Perseid Fireball

Spectroscopy Can Identify Likely Carbonaceous Asteroids

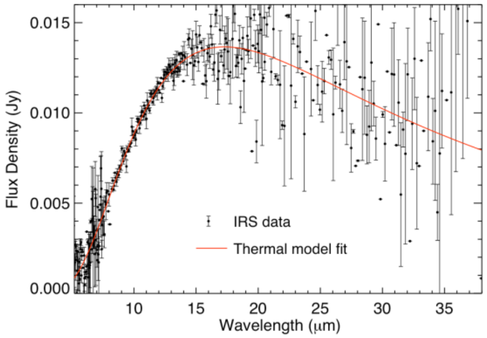


Lightcurve of (54509) YORP



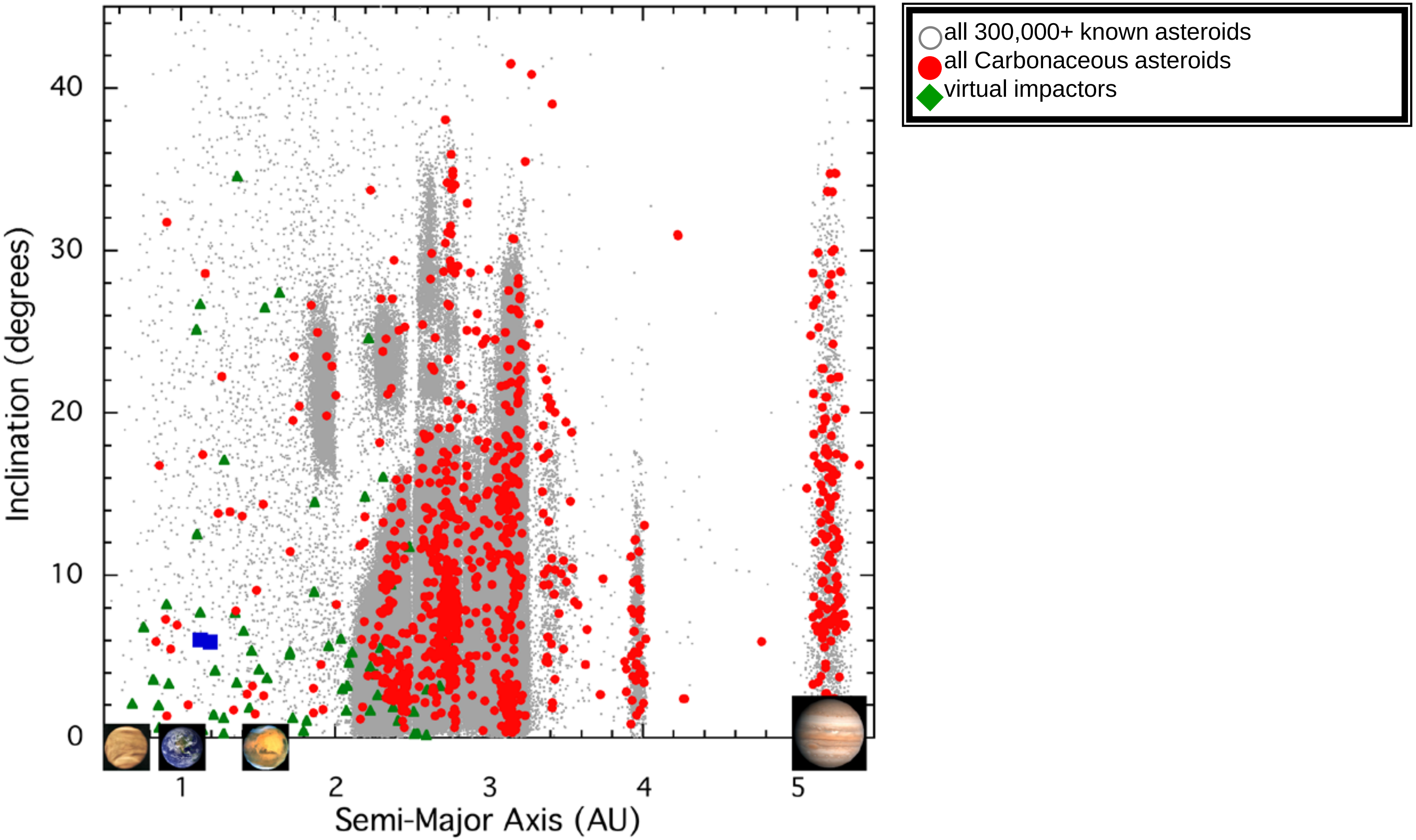
Rotation Period vs.
Diameter for all Asteroids

Visible Photometry	*Lightcurve* - rotation period, simple shape model, non-principal axis rotation, evidence of satellites, heterogeneity of surface *Colors* - taxonomy, rough mineralogy *Phase Function* - brightness, rough size, rough albedo, evidence of regolith
Visible Spectroscopy	*Spectroscopy* - taxonomy, mineralogy, heterogeneity of surface
Near-Infrared Spectroscopy	*Spectroscopy* - taxonomy, mineralogy, heterogeneity of surface, albedo of dark objects
Thermal Infrared Spectroscopy	*Spectroscopy* - mineralogy, heterogeneity of surface, albedo, size, thermal inertia, evidence of regolith

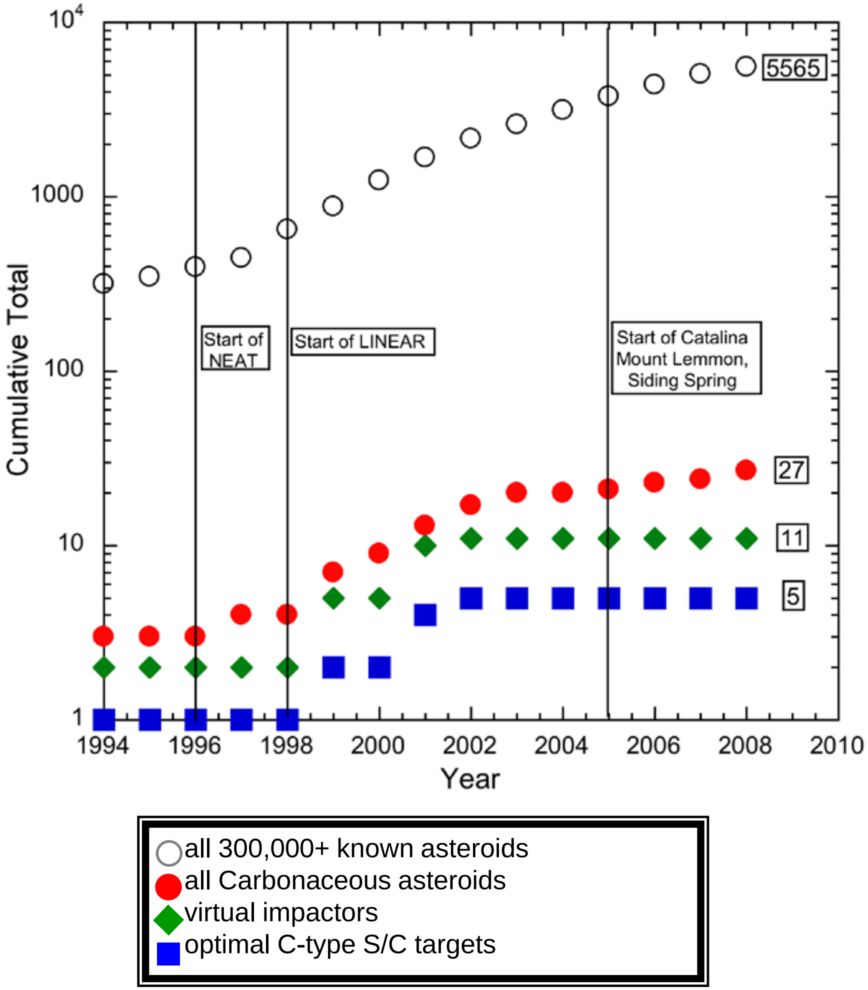


Spitzer Thermal Infrared Spectra
For a Typical Carbonaceous NEA

Carbonaceous Asteroids are Found Throughout the Inner Solar System…



Future Surveys are Unlikely to Discover a Large Number of Accessible Targets



Number of known NEAs has increased greatly after the advent of wide-field CCD surveys

Number of asteroids in optimal orbits greatly increased between 1996 and 2002

Increase in number of optimal asteroids has slowed since 2002 even though the capabilities of the surveys has improved (fainter limiting magnitude, extension to Southern Hemisphere)

Though the number of NEAs continues to climb, the discovery of optimal objects is slowing.
Most of the big objects have been found

16 of the 27 objects in optimal orbits are unclassified

Physical characterization of unclassified asteroids will increase the number of optimal carbonaceous objects by 2x to 3x

For Planetary Exploration: Energy = delta-V = Propulsion

- Chemical Propulsion
  - Hydrazine (N_2H_2) plus oxidizer
  - Carbonaceous asteroids contain N-bearing organic compounds
  - May be able to synthesize hydrazine *in situ*
  - Chemical processing needs to be developed

- Ion Propulsion
  - Xe plus power
  - Xe and other noble gases are energy resources in the Solar System
  - All asteroids contain measurable quantities of these elements
  - Chemical separation is easy (requires heat)

The Propulsion System Design is Critical for Reaching Important Targets

- Engineering Implications: proximity operations and landing scenarios, solar array or tank size and mass, and variation in launch C3

Subsystem	Chemical	Low-Thrust
Propulsion Specification	Bi-Prop ‘two’ engines @ 440N Isp = 320s	Electric Propulsion Four NEXT Engines @ 200mN, Isp = 4000s
Propulsion Power (kW)	~0.1	~30
Fuel Mass as a Function of S/C Wet mass (Rocket eqn)	1999 JU3 – 60% Apophis – 72%	1999 JU3 – 21% Apophis – 15%
Fuel Volume (m^3) Based on 2000kg wet mass	1999 JU3 – 1.12 Apophis – 0.67	1999 JU3 – 0.32 Apophis – 0.22
Operations	Small chemical for ProxOps & ACS	Small chemical for ProxOps & ACS

Low-thrust Missions Generally Have Shorter Duration

Comparison of Key Design Parameters

	Chemical Propulsion				**Low-Thrust Propulsion**			
	Launch C3 (km^2/s^2)	**ΔV (km/s)**	**Prop Mass (kg)**	**Days in Trip (days)**	**Launch C3 (km^2/s^2)**	**ΔV (km/s)**	**Prop Mass (kg)**	**Days in Trip (days)**
1999 JU3	25.5	2.9	2425	1827	9.9	9.3	1112	1448
Wilson-Harrington	20.0	2.7	2567	3589	33	7.7	662	4020
Apophis	16.7	4.0	3784	2525	0.4	6.6	962	1737
1989 UQ	13.3	4.6	3856	749	43	7.6	500	690

Asteroid Resources are Increasingly Accessible

- Real need exists for extension of Asteroid Surveys beyond orbit determination to include physical characterization
  - The NEOs contain a wealth of interesting targets yet only ~10% are well characterized
- The chemistry of carbonaceous asteroids is diverse
  - Increasing analytical capabilities reveal significant differences in the organic chemistry of individual specimens
  - You don’t know what you are going to get until you get there
- Solar Electric Propulsion opens up a new class of Energy Minerals – the Noble Gases

Reference

Pizzarello, S. and W. Holmes, 2009, Nitrogen-containing compounds in two CR2 meteorites: ^{15}N composition, molecular distribution and precursor molecules: Geochimica et Cosmochimica Acta, v. 73/7, p. 2150-2162. doi:10.1016/j.gca.2009.01.022