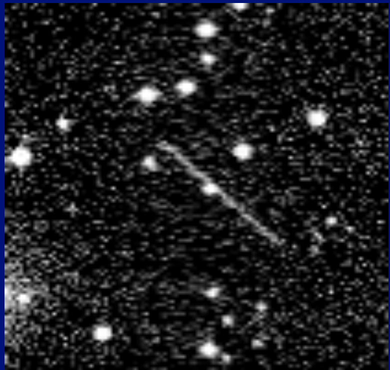
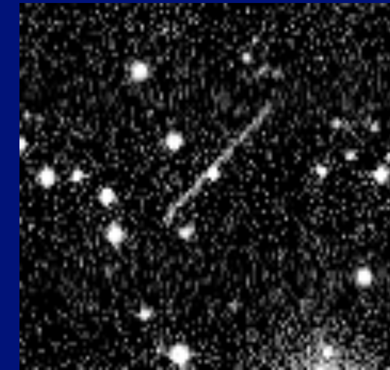




Spectral Reconnaissance of Near-Earth Objects

Professor Richard P. Binzel
Department of Earth, Atmospheric, and Planetary Sciences
Massachusetts Institute of Technology

NEO Warning & Mitigation:
Reasonable Measurement Objectives

- Size, shape
- Mass, density
- Internal structure
- Composition
- Rotation rate
- Spin state

NEO Science:
Measurement Objectives

- Size, shape
- Mass, density
- Internal structure
- Composition
- Rotation rate
- Spin state

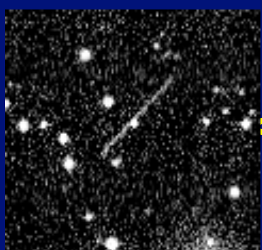
Finding #1:

Physical measurements for hazard assessment *are the same as* measurements of science interest.

Uncertainty Upon Discovery

Big and dark.

Assumed albedo = 0.04



Apparent brightness --->H magnitude

Which is it?

Assumed albedo = 0.34

Small and bright.

- Must have **color, albedo,** or **radar** information to know the size.
- Otherwise there is up to 300% uncertainty in the diameter.
- Diameter uncertainty creates factor of 20 uncertainty in energy.

Finding #2:

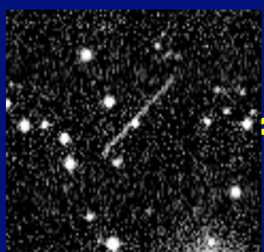
Physical observations are *required* in conjunction with discovery for hazard and warning assessment.

Uncertainty Upon Discovery

Big and dark.

Assumed albedo = 0.04

Which is it?



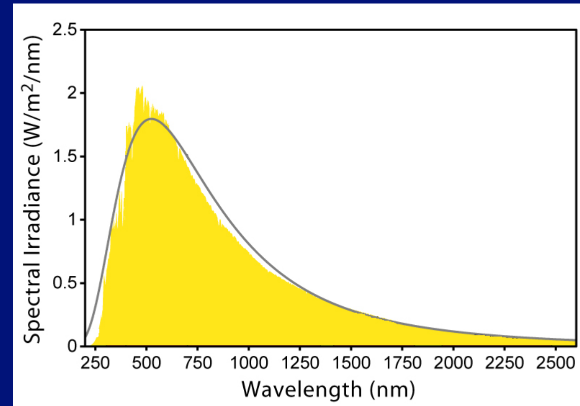
Apparent brightness --->H magnitude

Small and bright.

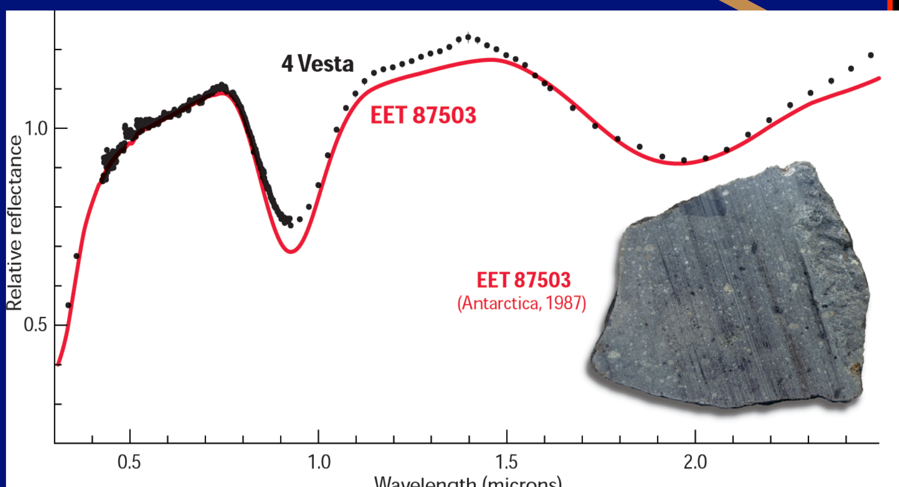
Assumed albedo = 0.34

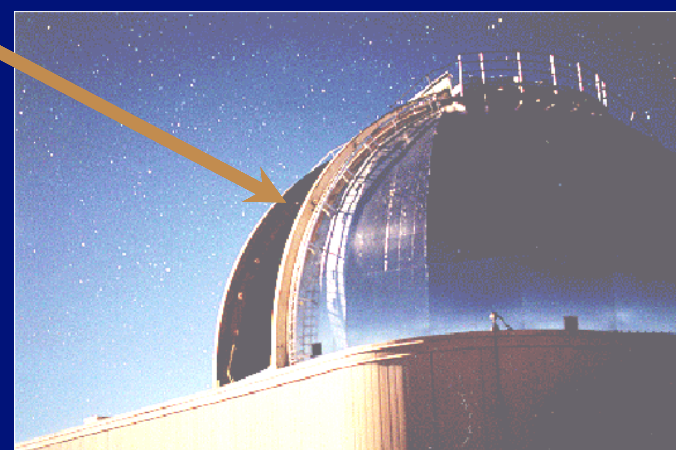
•Must have **color**, **albedo**, or **radar** information to know the size.

How Does It Work ?



Ratio between the Solar Spectrum and the Reflected Spectrum reveals the composition.





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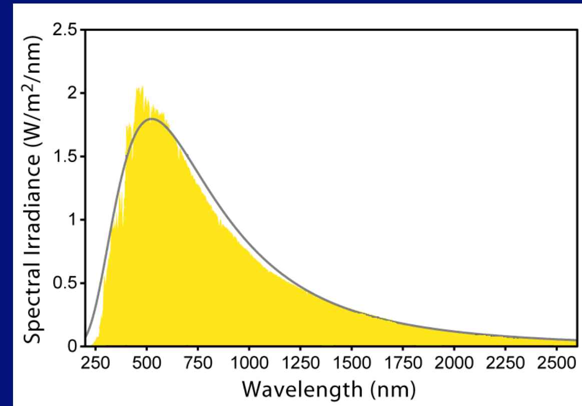

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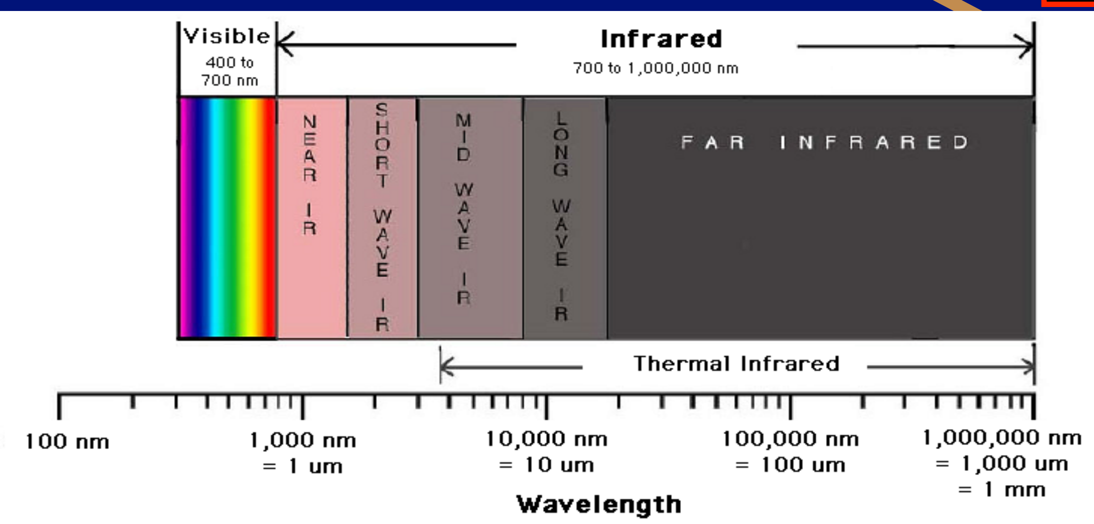

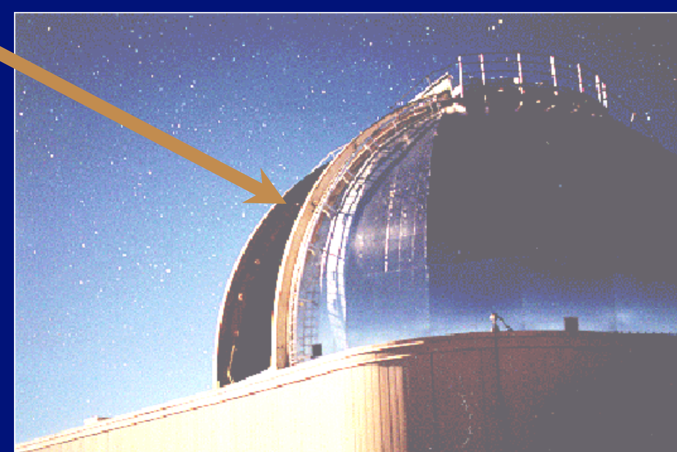

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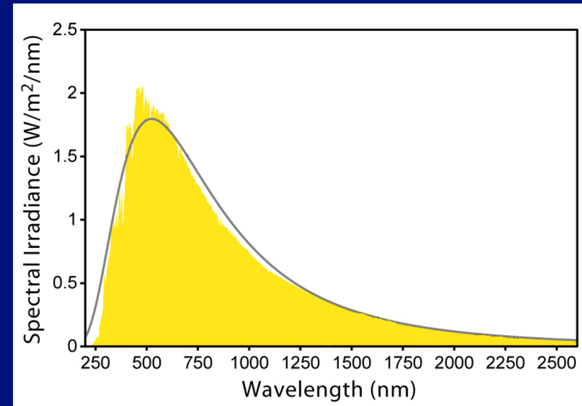

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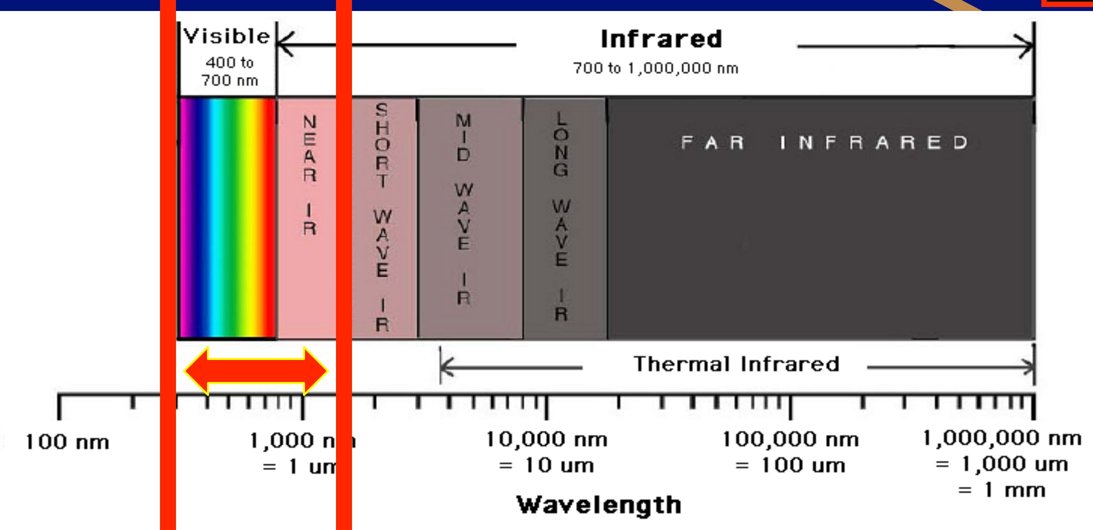
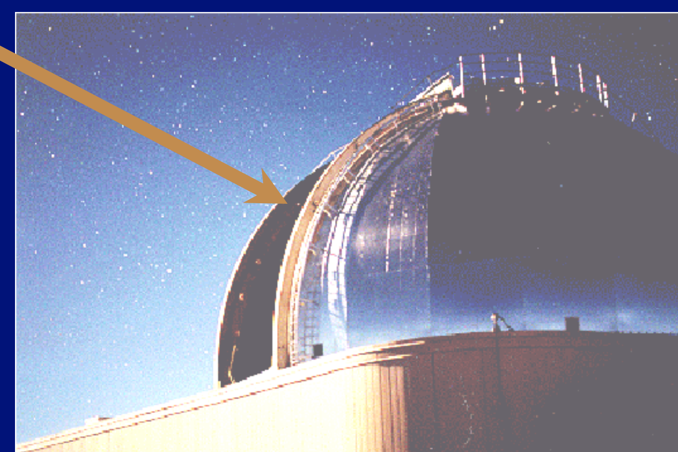




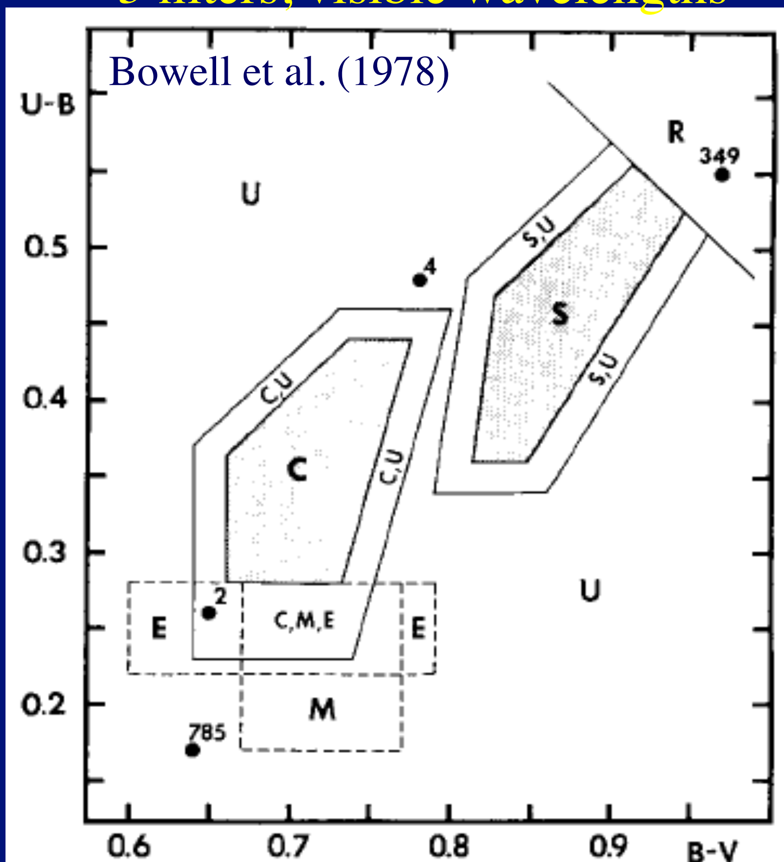
Asteroids Grouped by Color

ICARUS 35, 313–335 (1978)

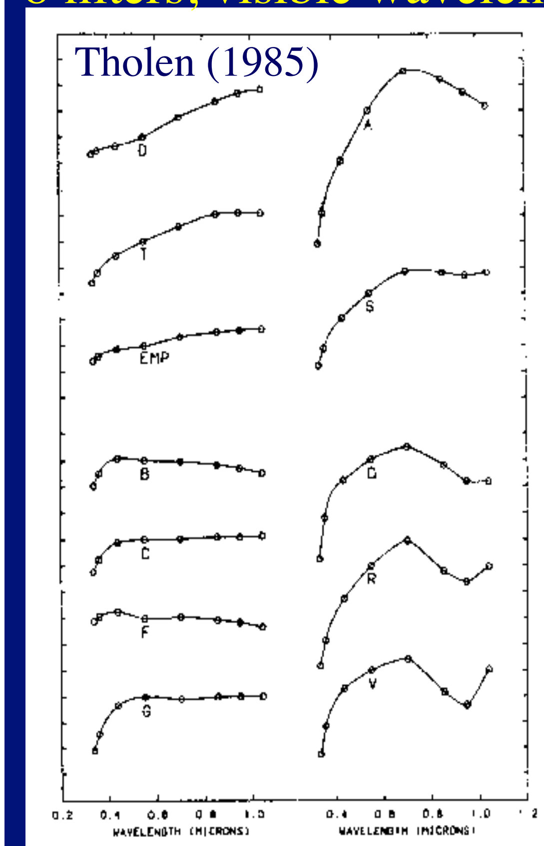
Taxonomy of Asteroids

EDWARD BOWELL,* CLARK R. CHAPMAN,† JONATHAN C. GRADIE,‡
DAVID MORRISON,§ AND BENJAMIN ZELLNER‡

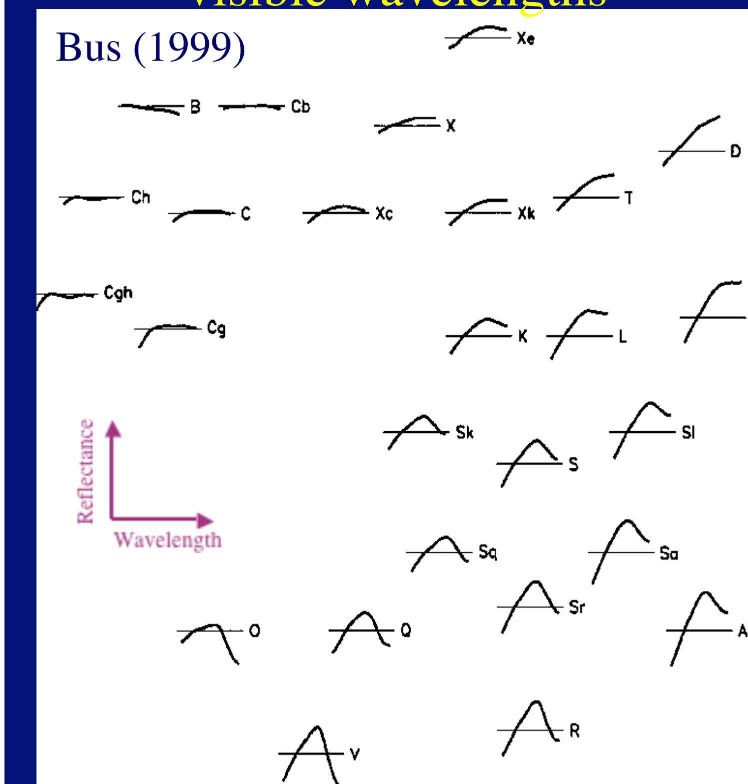
3 filters, visible wavelengths



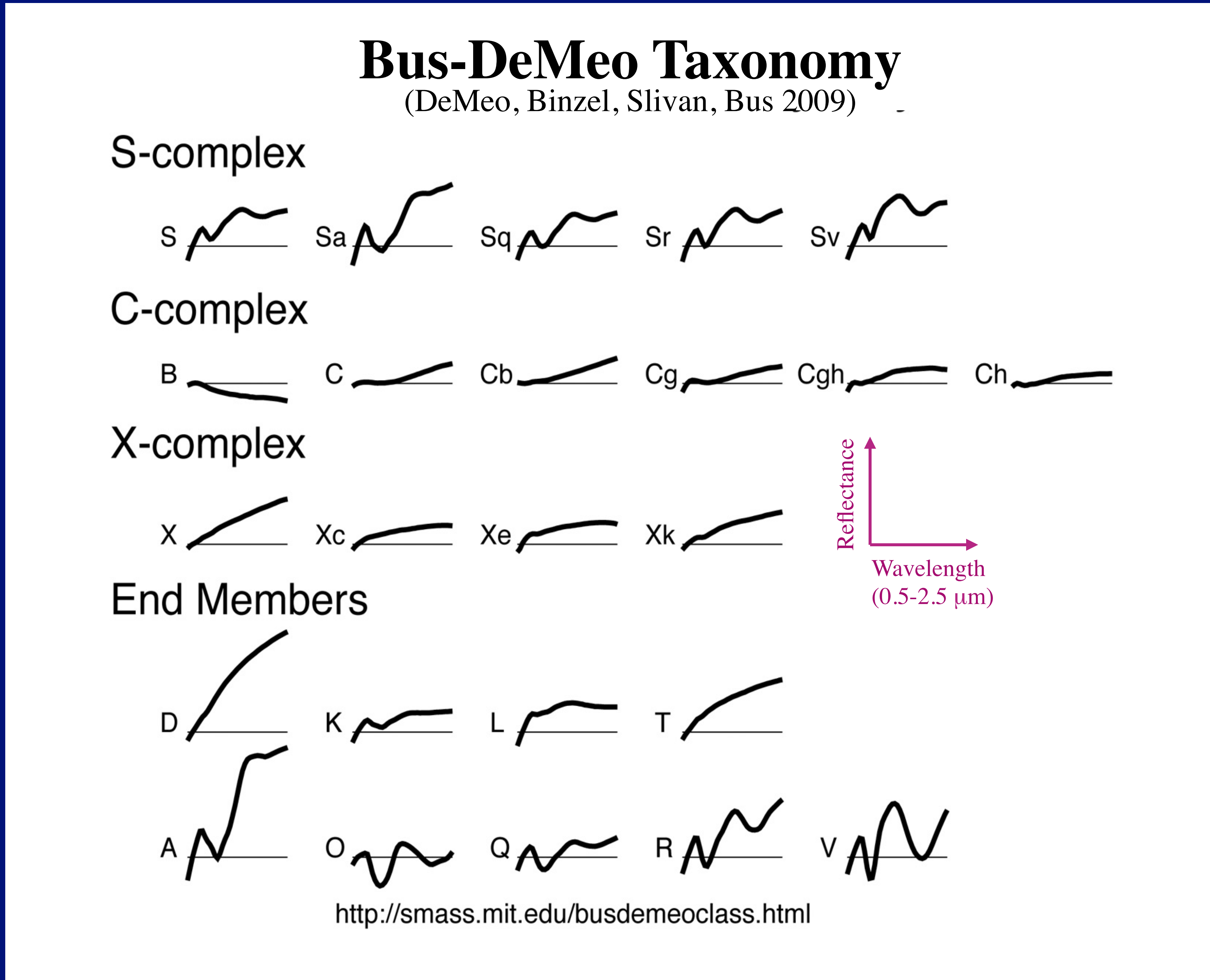
8 filters, visible wavelengths



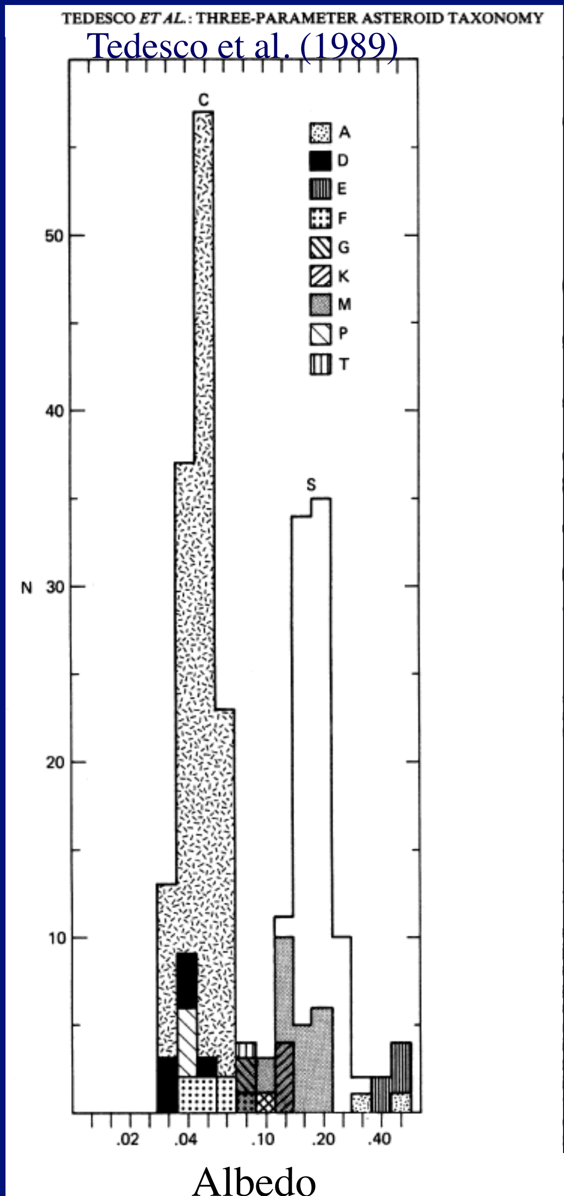
49 spectral channels, visible wavelengths



42 spectral channels, visible + near infrared (0.5 - 2.5 microns)

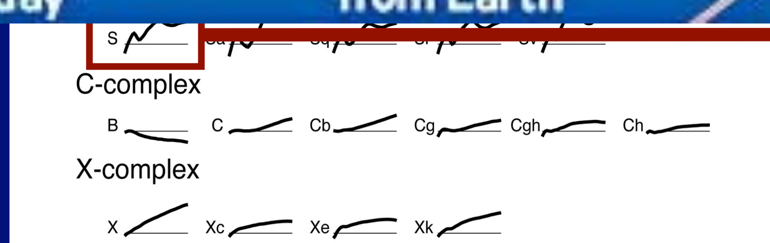


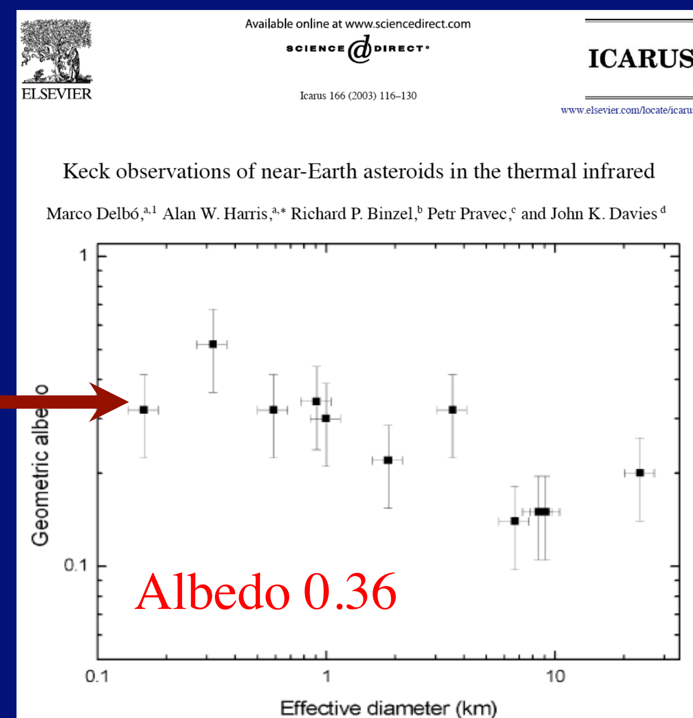
Colors Can Indicate Albedo

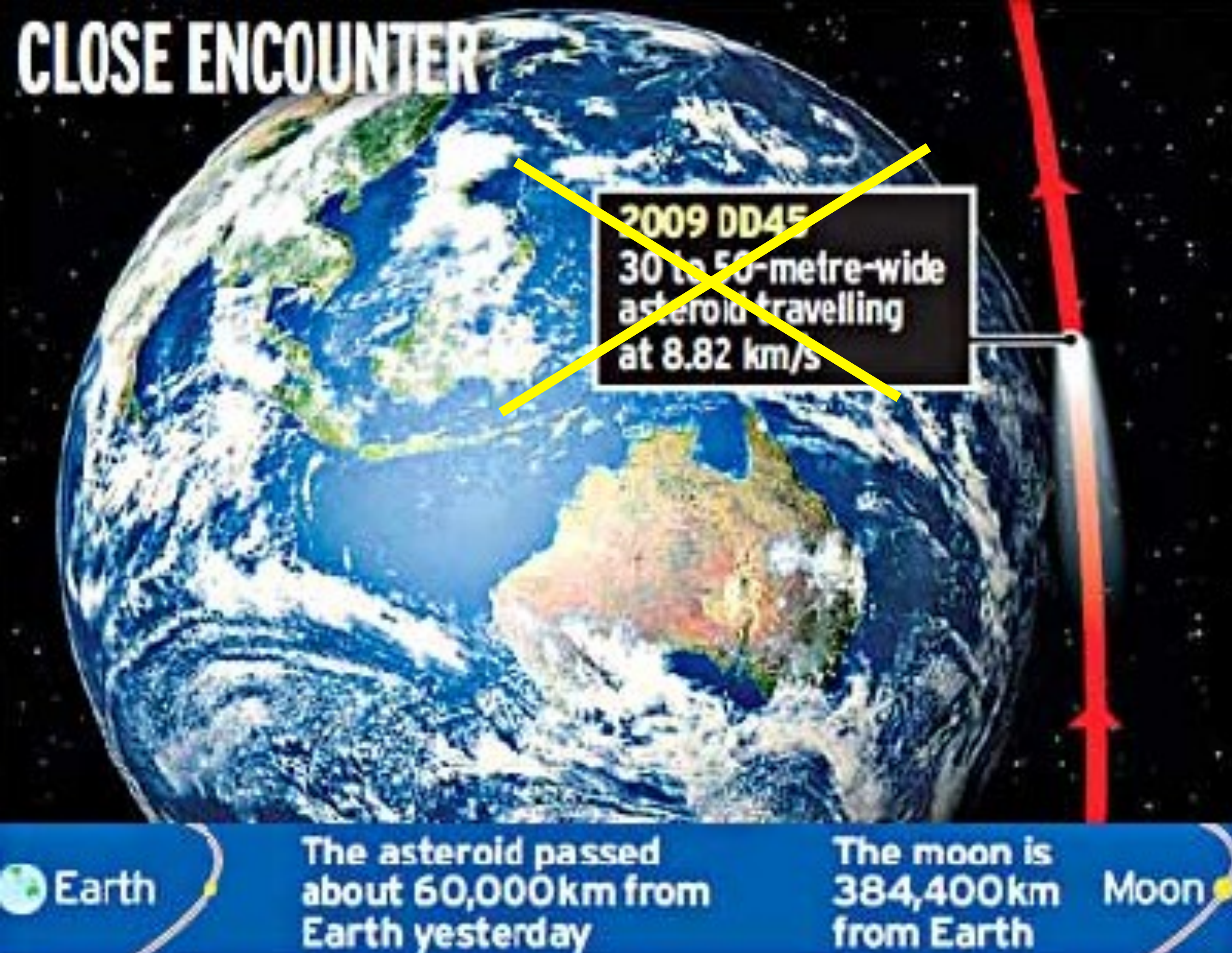


- There is a strong **correlation** between color group (taxonomy alphabet type) and albedo.
- Therefore, by grouping by **colors**, we can constrain the albedo.
- By **constraining** the **albedo**, we **reduce** the **uncertainty** in the **size** estimate.

Case Study #1
2009 DD45







2009 DD45

19 ± 4 meters

Circular No. 9024

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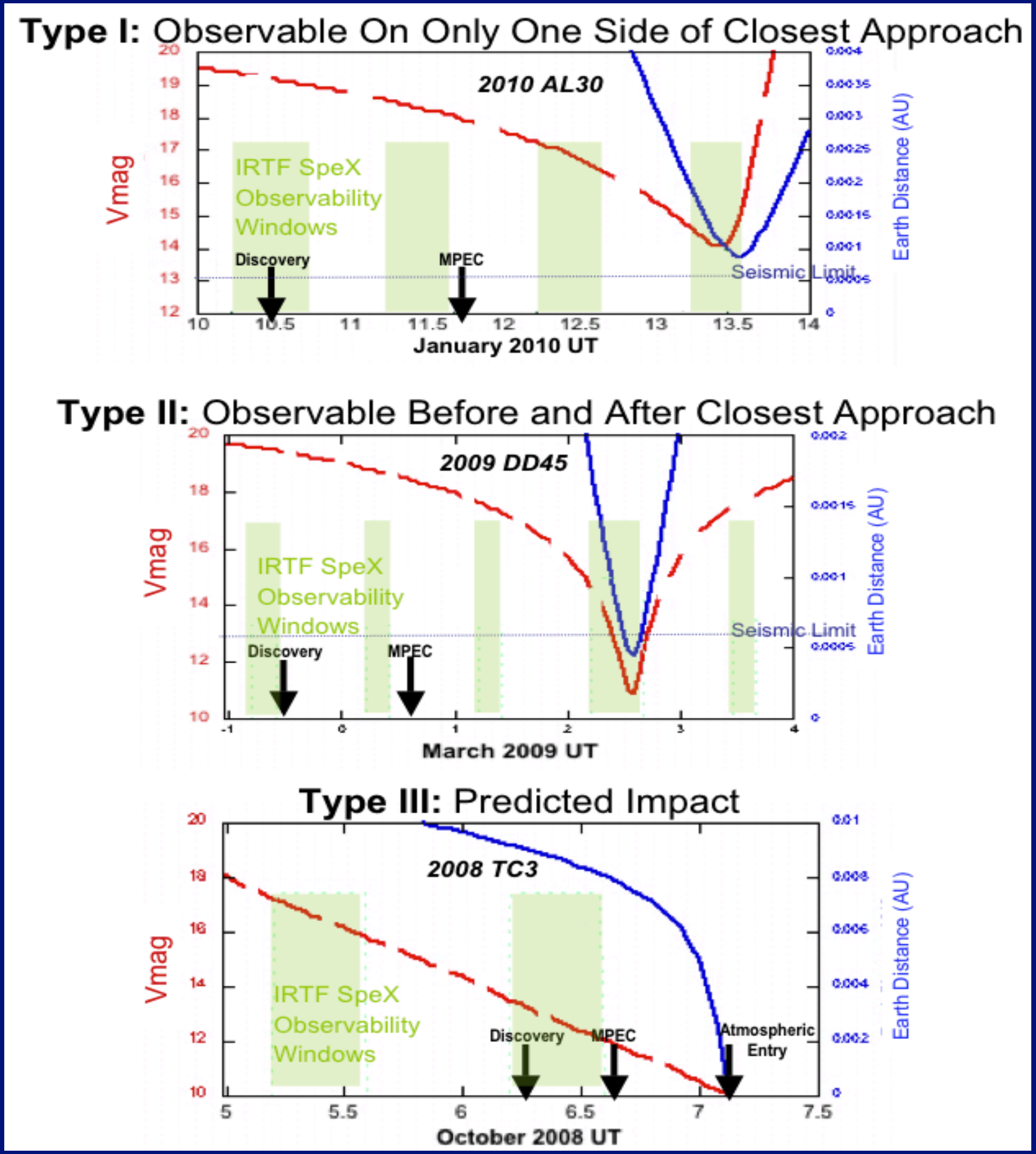
URL http://www.cfa.harvard.edu/iau/cbat.html ISSN 0081-0304
Phone 617-495-7440/7244/7444 (for emergency use only)

2009 DD_{45}

R. P. Binzel, M. Birlan, and F. E. DeMeo, Paris Observatory, report on their 0.8- to 2.5-μm spectroscopic measurements of 2009 DD_{45} (cf. *MPEC* 2009-D80) on Mar. 2.6 UT using the NASA Infrared Telescope Facility 3-m reflector on Mauna Kea. Absorption bands revealed at 1 and 2 μm show the characteristics of the S-type class of minor planets. Using the average albedo value of 0.36 for small near-earth objects in this class (Delbo *et al.* 2003, *Icarus* **166**, 116), and based on its H magnitude (25.4), the mean diameter is estimated to be 19 ± 4 m. The Apollo-type object passed only 0.000482 AU from the earth on Mar. 2.57 (cf. *MPEC* 2009-E10).

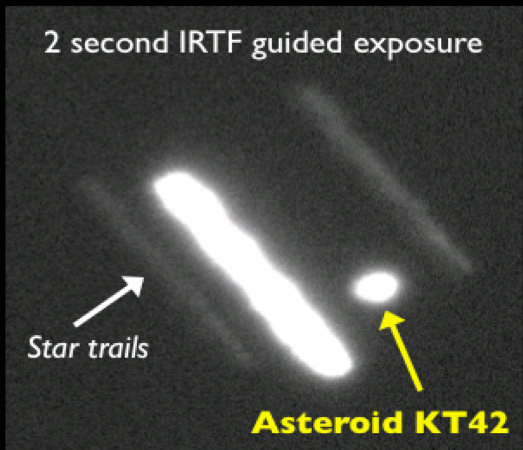
IRTF NEO Rapid Response Program*



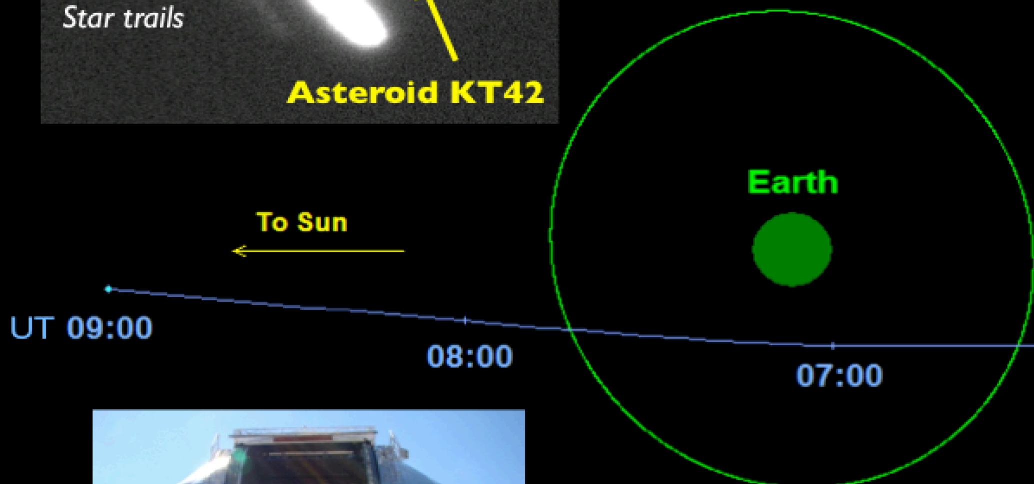
Co-Investigators: R. Binzel (MIT), N. Moskovitz (Lowell), T. Spahr (MPC), S. Chesley (JPL), S. J. Bus (UH), M. Birlan (Paris Obs)

Near-Earth Asteroid Close Approach Observed

Asteroid 2012 KT42: Encounter with Earth, May 29, 2012



- Discovery of asteroid triggered the existing NEO "target-of-opportunity" project at the NASA Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii, with the flexibility and capability to track near-Earth asteroids
- Closest approach of asteroid was within 9,200 miles of Earth's surface
- Observations determined asteroid's characteristics and hazard potential: At ~7 meters across, fragments unlikely to survive atmospheric passage



- Records were set at IRTF during this encounter for tracking speed and for closest object ever observed
- Movie on *Nature* website was #2 in hits for the week
- Another asteroid, 2012 KP24, approached to within 32,000 miles of Earth and was similarly observed from IRTF on May 28, 2012

2012 KT42 Timeline

T-23 hours: Discovery by Mt. Lemmon Observatory
T-18 hours: Alerts sent and IRTF notified
T-13 hours: IRTF interrupt formally requested
T-11 hours: IRTF interrupt approved
T-1 hour: Asteroid above horizon, IRTF measurements begin
T-25 minutes: Tracking lock lost (5.6 R_{earth})
T=0: Closest approach at 3.3 R_{earth}

Binzel *et al.* 2012, *Nature* News, doi:10.1038/nature.2012.10873

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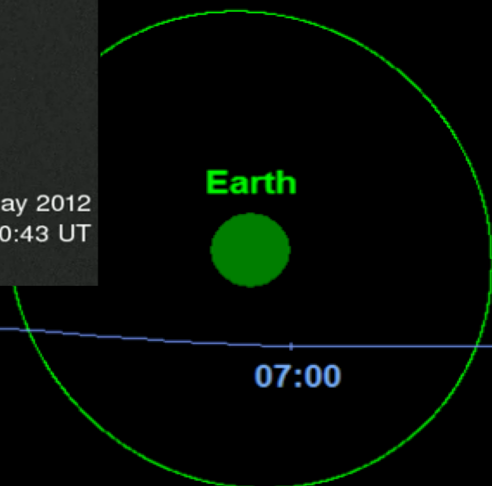

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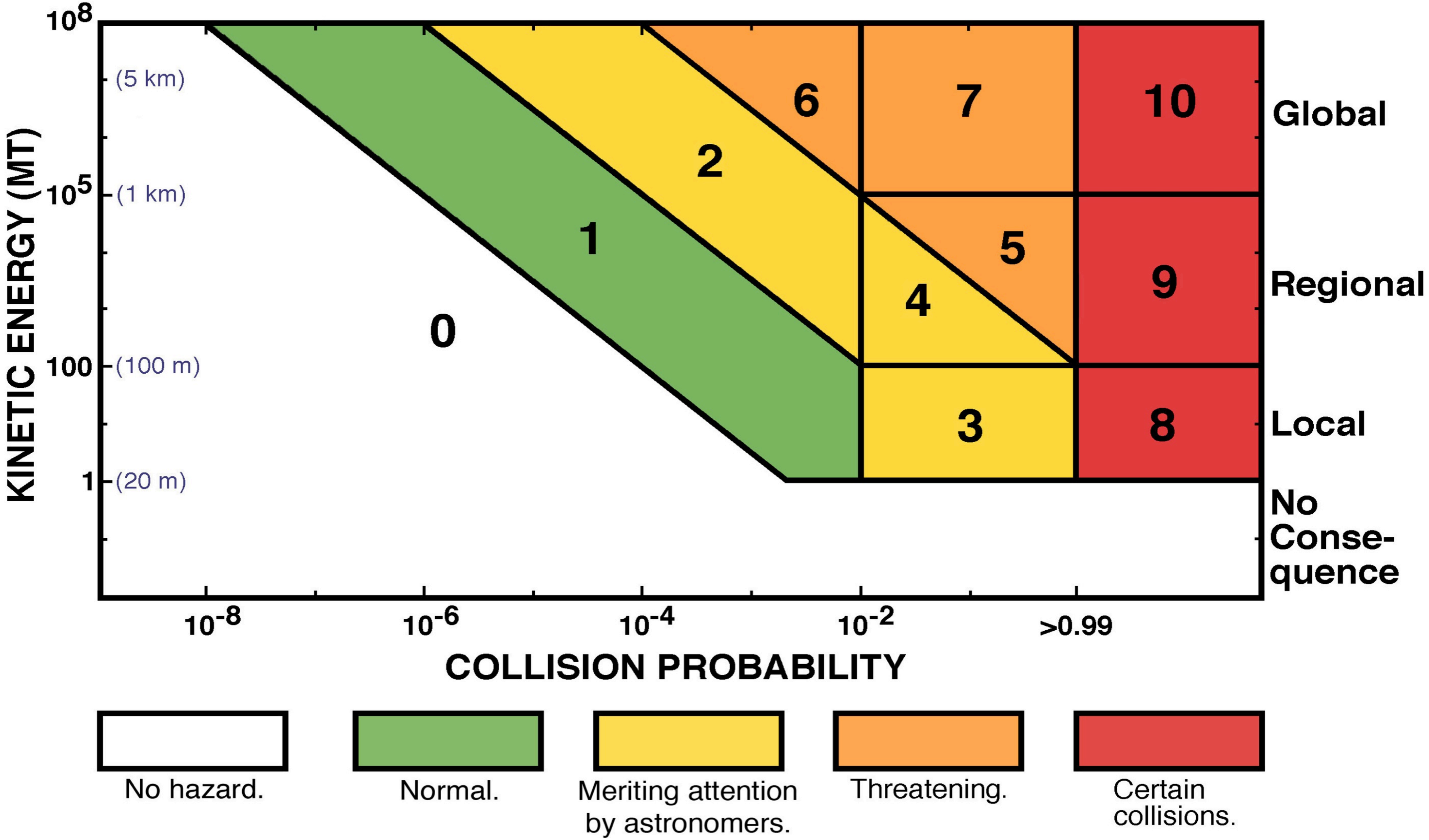
The Torino Scale

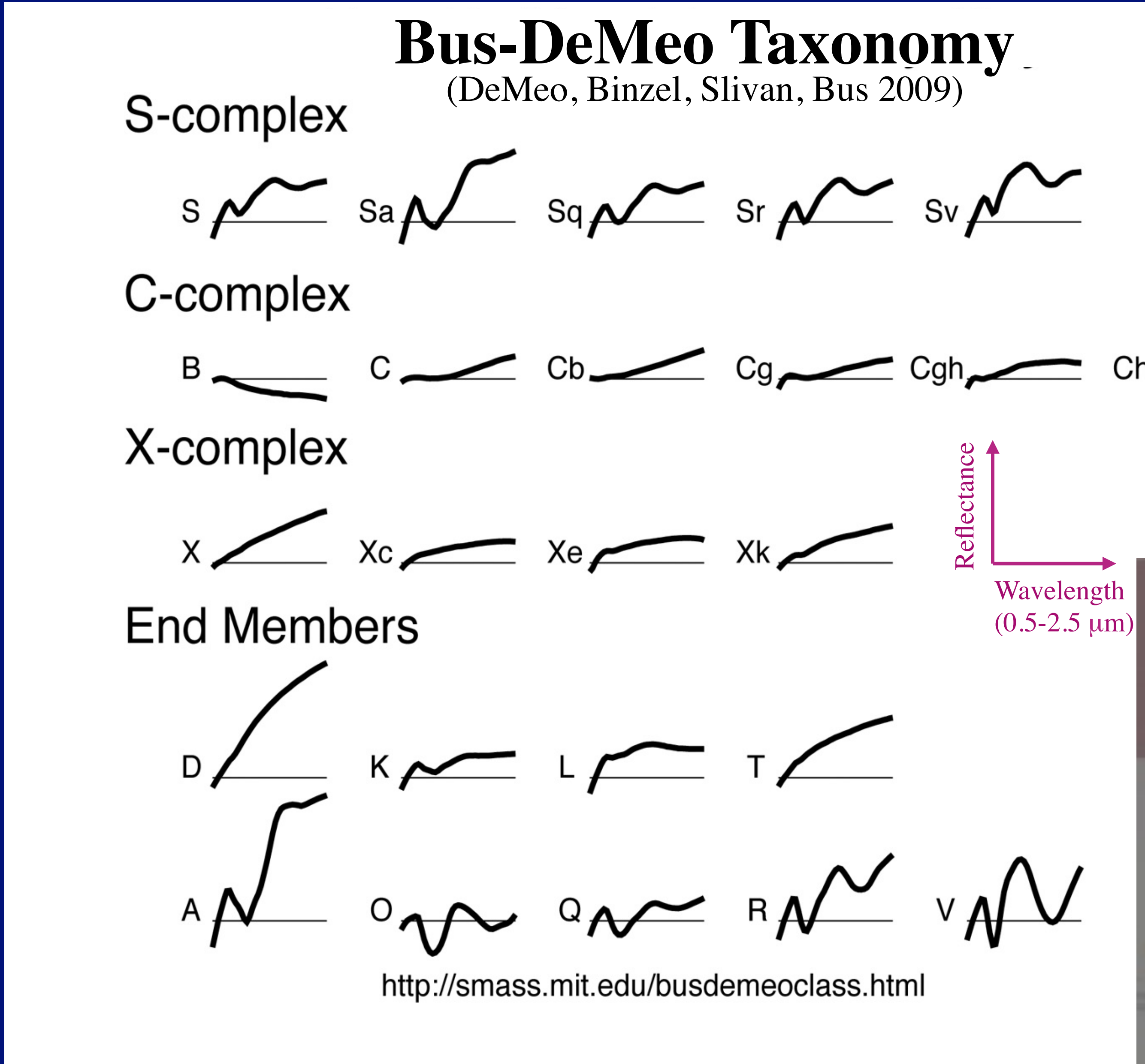


THE TORINO SCALE

Assessing Asteroid/Comet Impact Predictions

No Hazard	0	The likelihood of collision is zero, or is so low as to be effectively zero. Also applies to small objects such as meteors and bolides that burn up in the atmosphere as well as infrequent meteorite falls that rarely cause damage.
Normal	1	A routine discovery in which a pass near the Earth is predicted that poses no unusual level of danger. Current calculations show the chance of collision is extremely unlikely with no cause for public attention or public concern. New telescopic observations very likely will lead to re-assignment to Level 0.
Meriting Attention by Astronomers	2	A discovery, which may become routine with expanded searches, of an object making a somewhat close but not highly unusual pass near the Earth. While meriting attention by astronomers, there is no cause for public attention or public concern as an actual collision is very unlikely. New telescopic observations very likely will lead to re-assignment to Level 0.
	3	A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of localized destruction. Most likely, new telescopic observations will lead to re-assignment to Level 0. Attention by the public and by public officials is merited if the encounter is less than a decade away.
	4	A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of regional devastation. Most likely, new telescopic observations will lead to re-assignment to Level 0. Attention by the public and by public officials is merited if the encounter is less than a decade away.
Threatening	5	A close encounter posing a serious, but still uncertain threat of regional devastation. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur. If the encounter is less than a decade away, governmental contingency planning may be warranted.
	6	A close encounter by a large object posing a serious, but still uncertain threat of a global catastrophe. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur. If the encounter is less than three decades away, governmental contingency planning may be warranted.
	7	A very close encounter by a large object, which if occurring this century, poses an unprecedented but still uncertain threat of a global catastrophe. For such a threat in this century, international contingency planning is warranted, especially to determine urgently and conclusively whether or not a collision will occur.
Certain Collisions	8	A collision is certain, capable of causing localized destruction for an impact over land or possibly a tsunami if close offshore. Such events occur on average between once per 50 years and once per several 1000 years.
	9	A collision is certain, capable of causing unprecedented regional devastation for a land impact or the threat of a major tsunami for an ocean impact. Such events occur on average between once per 10,000 years and once per 100,000 years.
	10	A collision is certain, capable of causing a global climatic catastrophe that may threaten the future of civilization as we know it, whether impacting land or ocean. Such events occur on average once per 100,000 years, or less often.

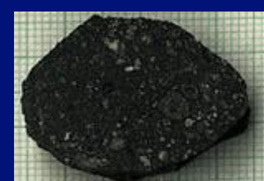
Spectral Reconnaissance



Size matters, but there's more . . .

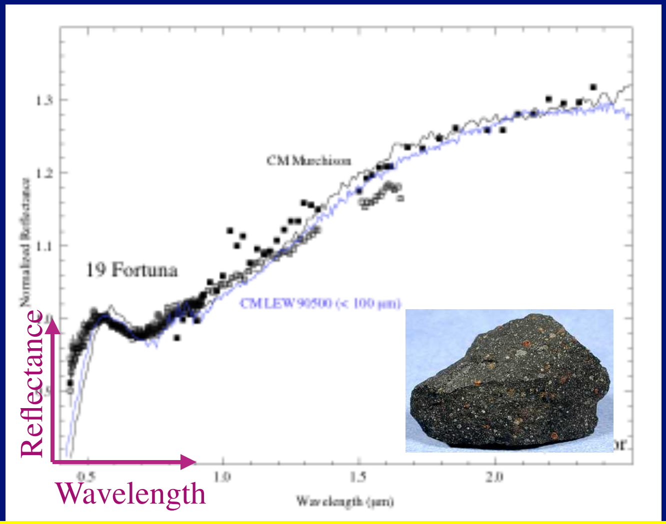
- Estimate the bulk physical properties such as mass, density.
- Estimating the bulk properties requires knowledge of the composition.
- Most detailed knowledge of composition comes from direct samples: **Meteorites !**



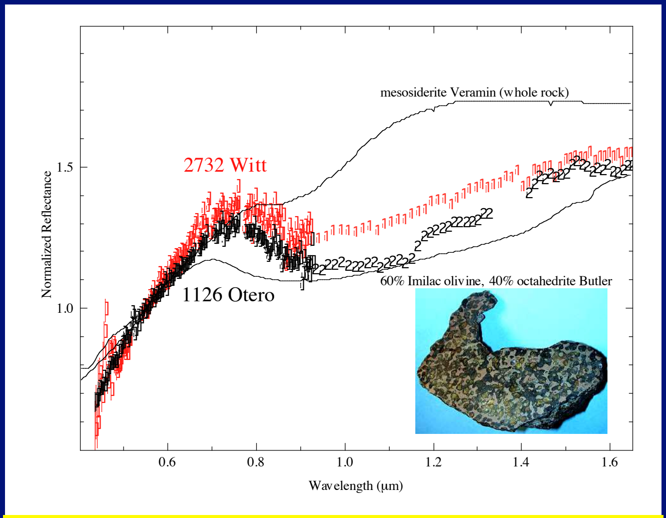




We have thousands of direct samples of NEOs in the form of Meteorites.

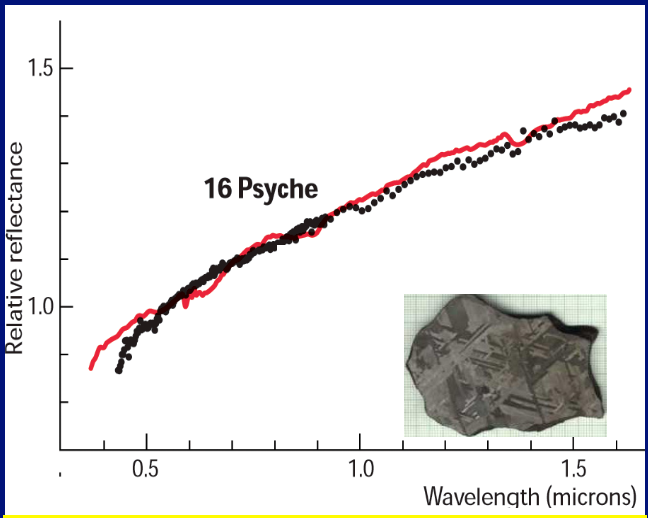
The Power of Reflectance Spectroscopy: Meteorite Analogs



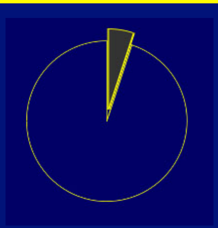
Carbonaceous
Albedo 0.05 - 0.10.
Density 2.1-3.1 g cm^{-3}



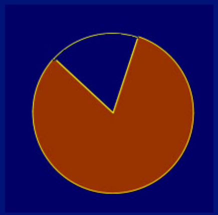
Chondrite or Stony Iron
Albedo 0.15 - 0.25.
Density 3.0-4.8 g cm^{-3}

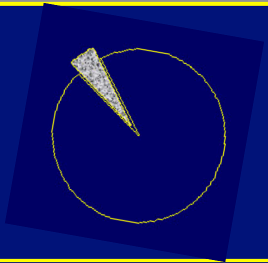


Iron
Albedo 0.10 - 0.20.
Density 7-8 g cm^{-3}



Percentage of all meteorite falls





Meteorite data from Britt & Consolmagno (2003). Asteroid data from Burbine (2000) Ph.D. Thesis M.I.T.

The Power of Reflectance Spectroscopy:

The Power of Reflectance Spectroscopy: Do we know what we are doing?

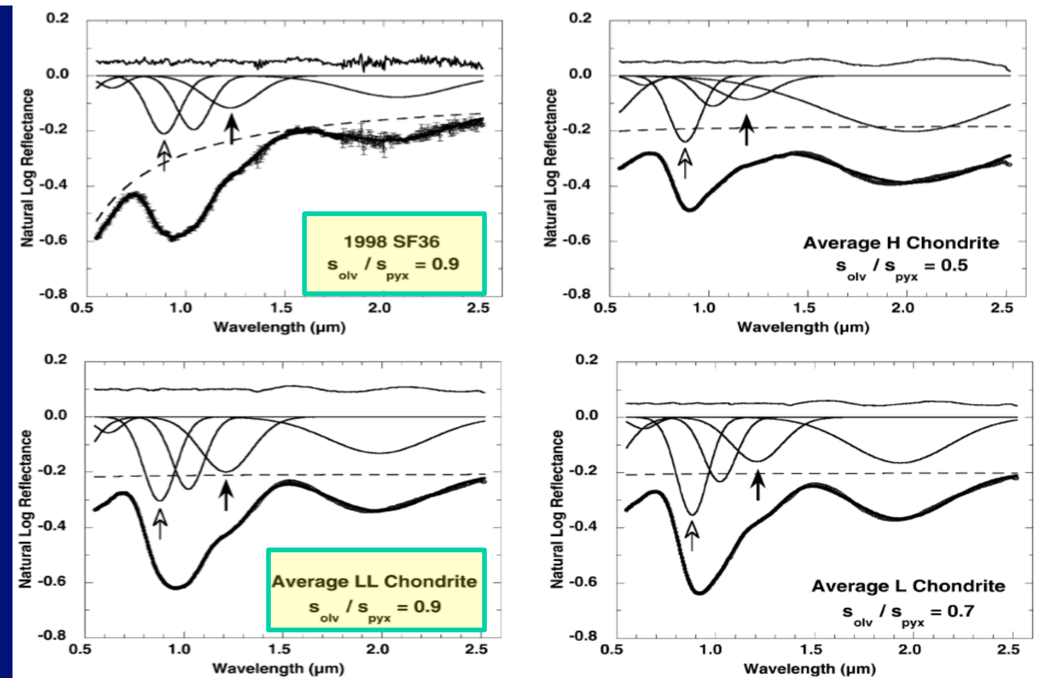
The Power of Reflectance Spectroscopy: Do we know what we are doing?

Meteoritics & Planetary Science 36, 1167–1172 (2001)

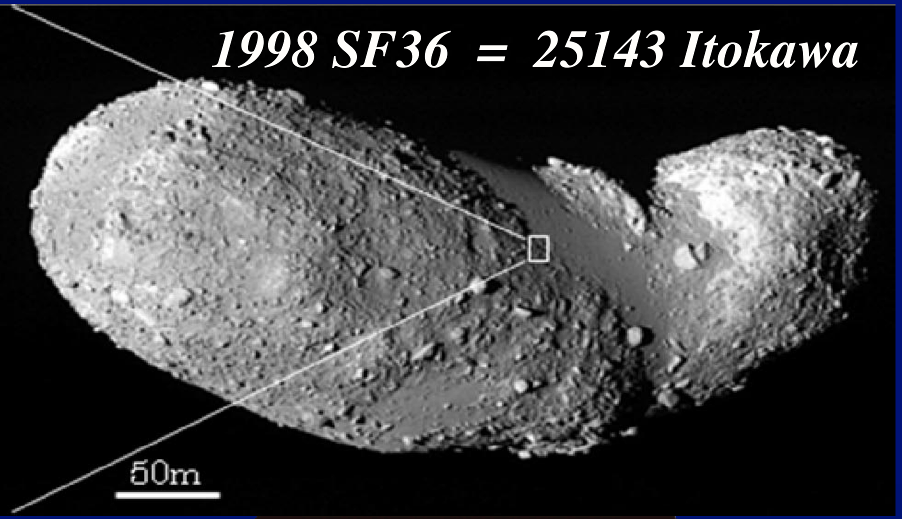
MUSES-C target asteroid (25143) 1998 SF36: A reddened ordinary chondrite

RICHARD P. BINZEL[1]*, ANDREW S. RIVKIN[1], SCHELTE J. BUS[2], JESSICA M. SUNSHINE[3] AND THOMAS H. BURBINE[4]

Abstract–Near-Earth asteroid (25143) 1998 SF36 is a planned target for the Japanese MUSES-C sample return mission. High signal-to-noise and relatively high-resolution (50 Å) visible and near-infrared spectroscopic measurements obtained during this asteroid's favorable 2001 apparition reveal it to have a red-sloped S(IV)-type spectrum with strong 1 and 2 μm absorption bands analogous to those measured for ordinary chond e meteorites. This red slope, which is the primary spectral difference between (25143) 199 and ordinary chondrite meteorites, is well modeled by the spectrum of 0.05% nanop ha (npFe^0) proposed as a weathering mechanism by Pieters *et al.* (2000). Asteroid 1998 S ars to have a surface composition corresponding to that of ordinary chondrite meteorites and i similar in spectral characteristics and modeled olivine/pyroxene content to the LL chondrite class.



The Power of Reflectance Spectroscopy: Do we know what we are doing?



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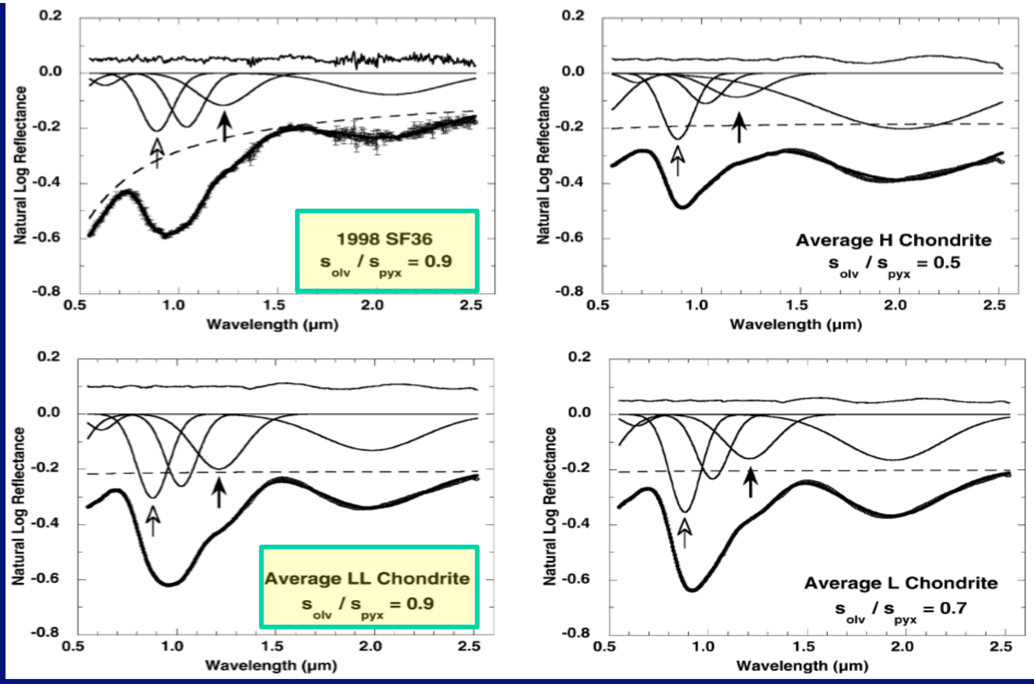

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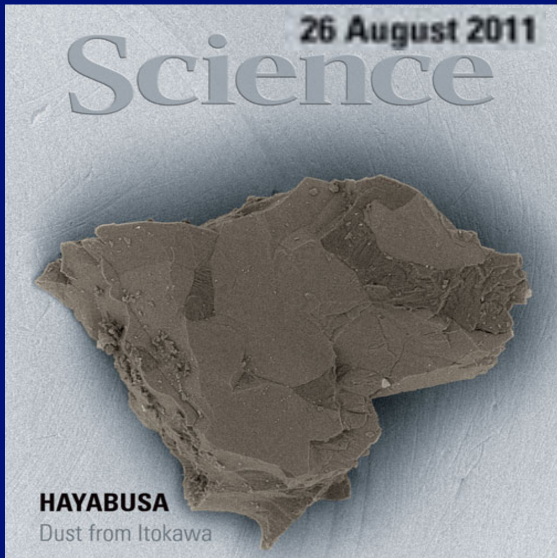

Itokawa Dust Particles: A Direct Link Between S-Type Asteroids and Ordinary Chondrites

Tomoki Nakamura,[1*] Takaaki Noguchi,[2] Masahiko Tanaka,[3] Michael E. Zolensky,[4] Makoto Kimura,[2] Akira Tsuchiyama,[5] Aiko Nakato,[1] Toshihiro Ogami,[1] Hatsumi Ishida,[1] Masayuki Uesugi,[6] Toru Yada,[6] Kei Shirai,[6] Akio Fujimura,[6] Ryuji Okazaki,[7] Scott A. Sandford,[8] Yukihiro Ishibashi,[6] Masanao Abe,[6] Tatsuaki Okada,[6] Munetaka Ueno,[6] Toshifumi Mukai,[6] Makoto Yoshikawa,[6] Junichiro Kawaguchi[6]

The Hayabusa spacecraft successfully re… particles from the surface of near-Earth asteroid 25143 Itokawa. Synchrotron-radiation x-ray dif… and transmission and scanning electron microscope analyses indicate that the mineralogy and mine…mistry of the Itokawa dust particles are identical to those of thermally metamorphosed LL chondrites, consistent with spectroscopic observations made from Earth and by the Hayabusa spacecraft. Our results directly demonstrate that ordinary chondrites, the most abundant meteorites found on Earth, come from S-type asteroids. Mineral chemistry indicates that the majority of regolith surface particles suffered long-term thermal annealing and subsequent impact shock, suggesting that Itokawa is an asteroid made of reassembled pieces of the interior portions of a once larger asteroid.

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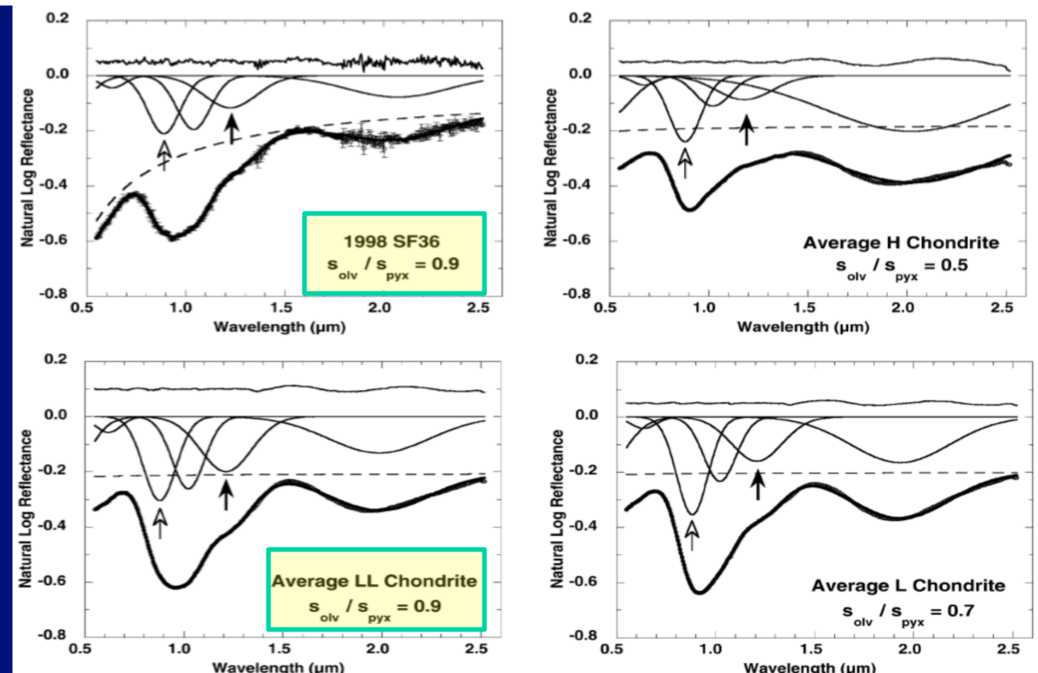
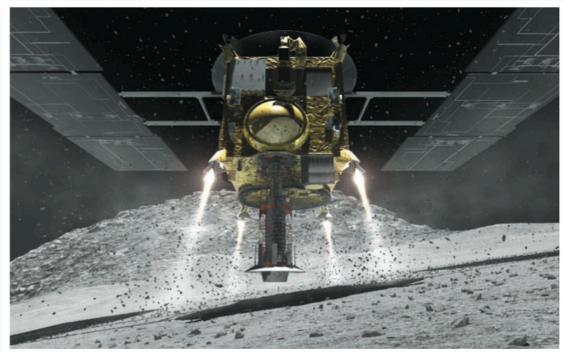


Asteroid Dust Solves Color Conundrum



Made it! Touchdown on Itokawa, as portrayed in the Japanese movie *Hayabusa: Back to the Earth.*

TITUTE FOR EVOLUTIONARY ANTHROPOLOGY

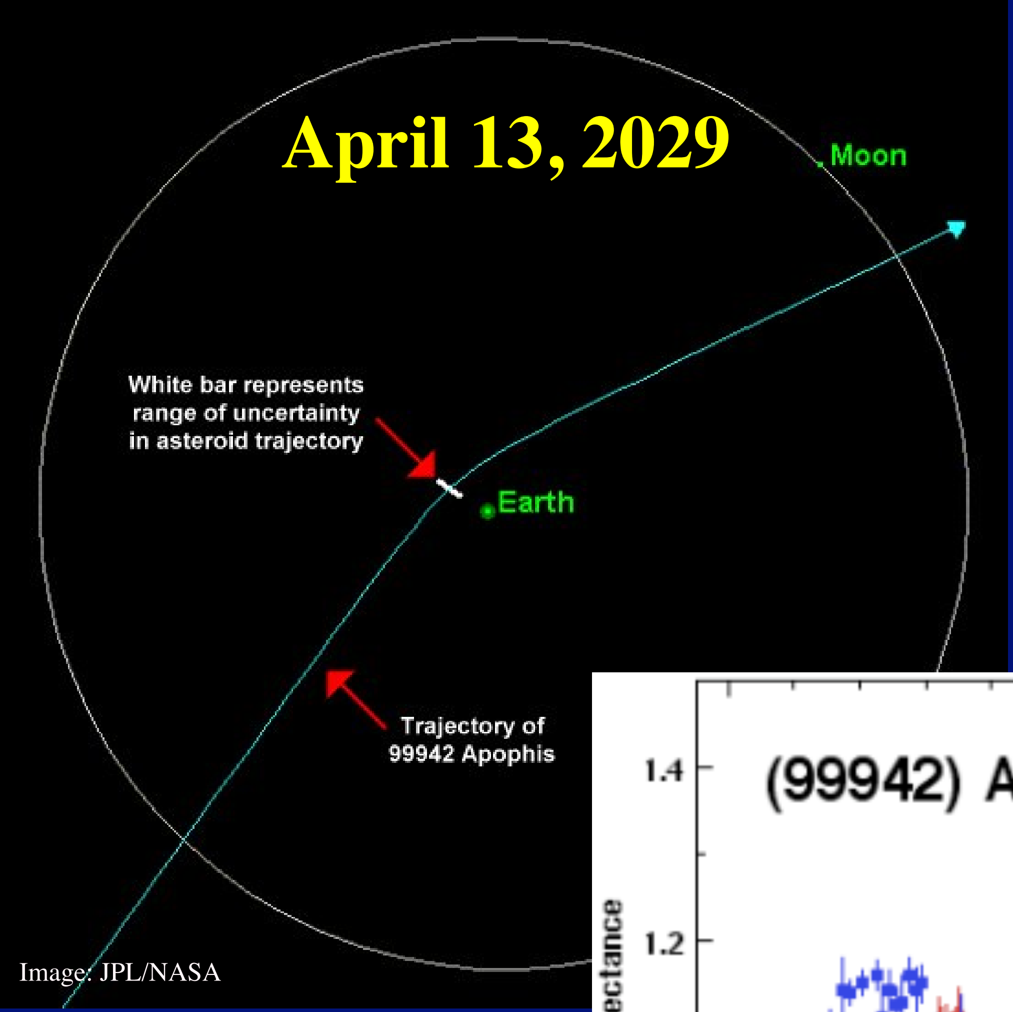
This year the first samples returned from another planetary body in 35 years settled a decades-old planetary mystery: why the most common meteorites that fall to Earth didn't seem to come from the most common asteroids in the asteroid belt. It turns out they do. By examining bits of asteroid Itokawa brought back by Japan's Hayabusa spacecraft, researchers discovered that the solar wind had been discoloring asteroids enough to cause a massive case of mistaken identity.

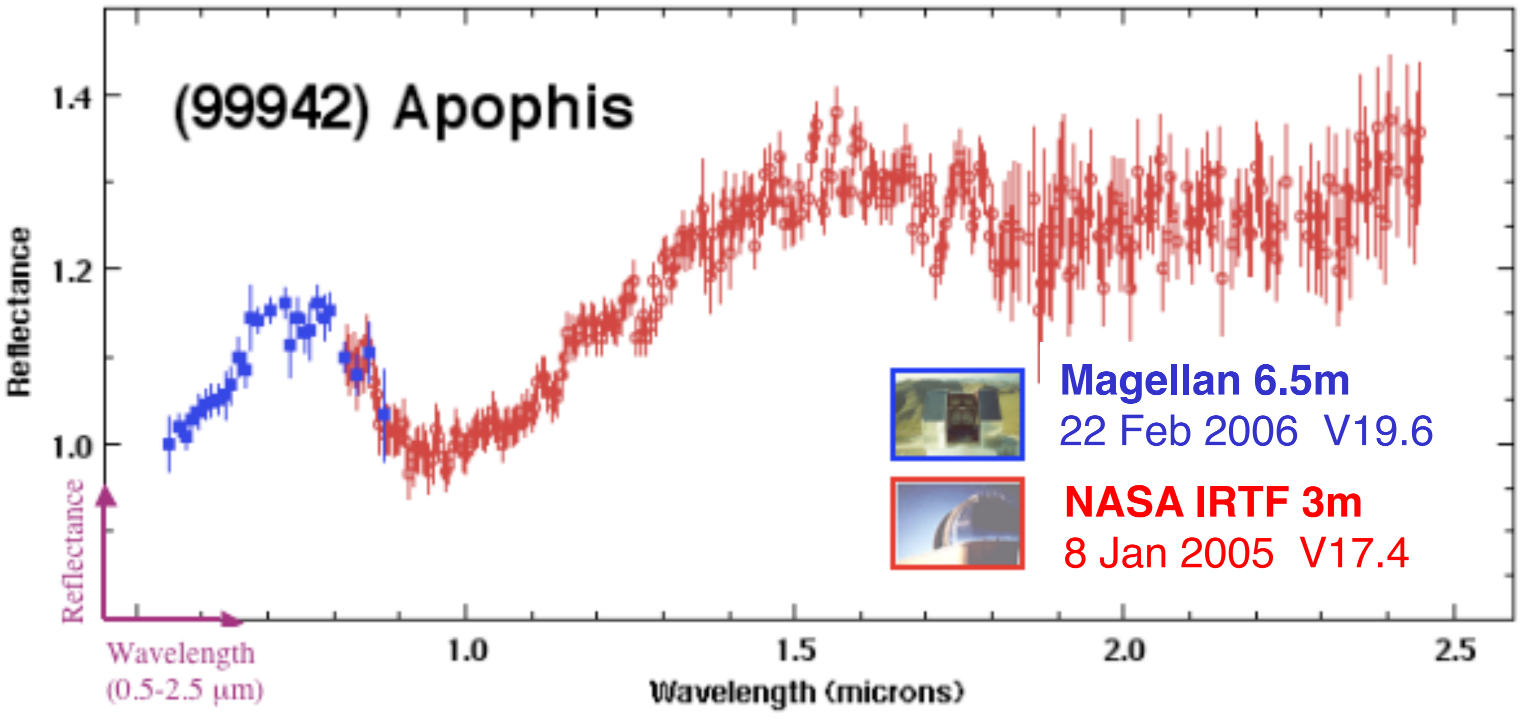
Hayabusa's odyssey to and from the 535-meter-long Itokawa was as harrowing as anything in Homer. En route, the spacecraft lost two of its three gyroscopelike reaction wheels that controlled its attitude, so it had to fall back on small rockets normally used for course corrections. A tiny rover meant to explore Itokawa's surface instead wound up being launched into deep space. Before the return trip, the spacecraft's attitude-control thrusters sprang a fuel leak; the spacecraft lost its proper orientation, breaking off communications, losing solar power, short-circuiting its batteries, and sinking into a deep freeze.

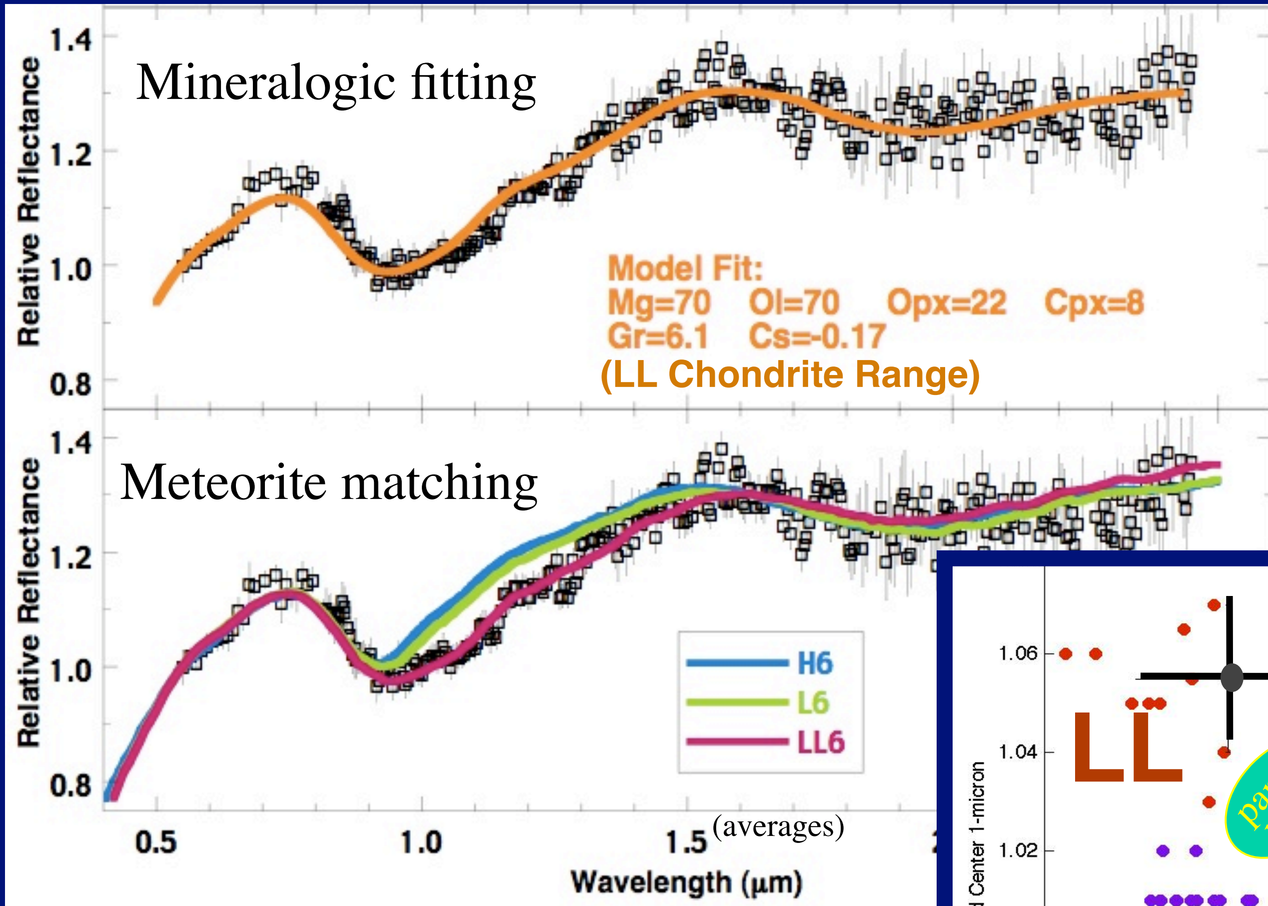
In a stunningly successful rescue mission, Hayabusa's controllers managed to pull the spacecraft back from the brink of disaster. It returned in June 2010, 3 years late and carrying only a dusting of Itokawa particles—but that was enough. Analyzing 52 particles, each less than 100 micrometers in diameter, Japanese researchers showed that the elements and minerals that make up Itokawa—a member of the largest class of asteroids, the S types—match the composition of the most abundant type of meteorite, ordinary chondrites. Researchers had long been inferring the composition of asteroids from their remotely recorded spectral colors. But the S types looked too red to be the source of the ordinary chondrites. Sophisticated spectroscopic analyses eventually showed that the tint was misleading and the link real. This year, Hayabusa's wispy cargo of asteroid dust closed the case for good.

Probing further, researchers used scanning transmission electron microscopy to look beneath the surface of Itokawa particles. There they could see tiny "nanoblobs" of metallic iron small enough to scatter sunlight and redden the asteroid's surface. Most of the nanoblobs probably formed when charged particles such as protons blowing in the solar wind penetrated the particles on Itokawa's surface. Mission accomplished, Hayabusa.

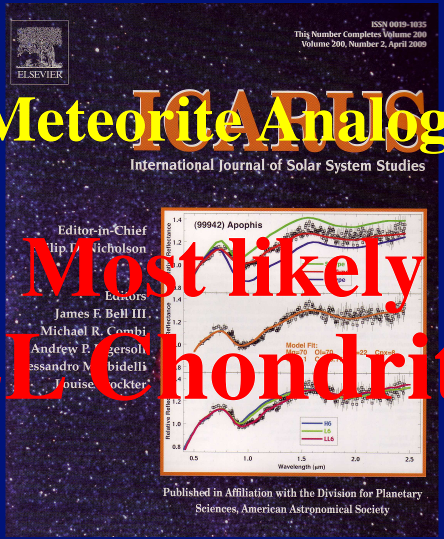
Case Study #2
(99942) Apophis





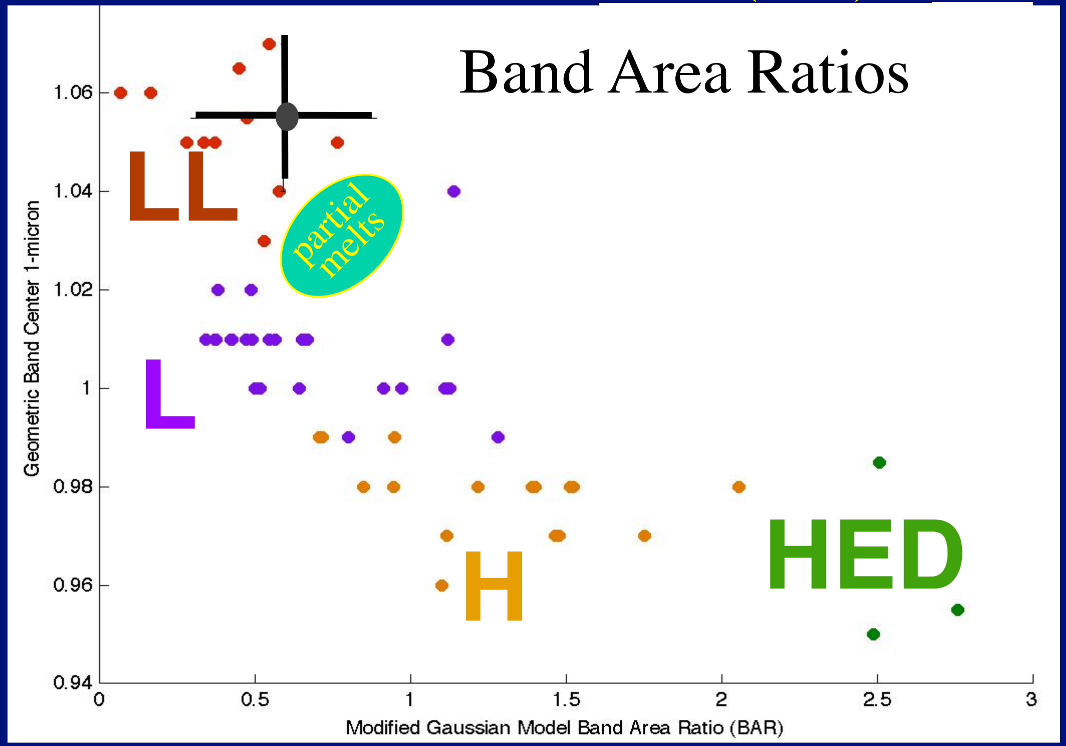


Meteorite Analog:



Most likely LL Chondrite

Binzel et al. (2009)



Apophis as an LL Chondrite

- Grain density 3.5 ± 0.1 g cm^{-3}
- Bulk density 3.2 ± 0.2 g cm^{-3}
- Micro-porosity 7.9 ± 4.2 %
- Composition is olivine, pyroxene, relatively low metal.
- For 270 m diameter [1], resulting mass estimate = 3.3 ± 1.5 x 10^{10} kg
- Corresponding energy in the range 500 ± 200 megatons.

[1] Current size estimate from Delbo et al. (2007).

Meteorite data from Britt & Consolmagno (2003).

Meteorite Link = First Line of Defense

- Grain density 3.5 ± 0.1 g cm^{-3}
- Bulk density 3.2 ± 0.2 g cm^{-3}
- Micro-porosity 7.9 ± 4.2 %
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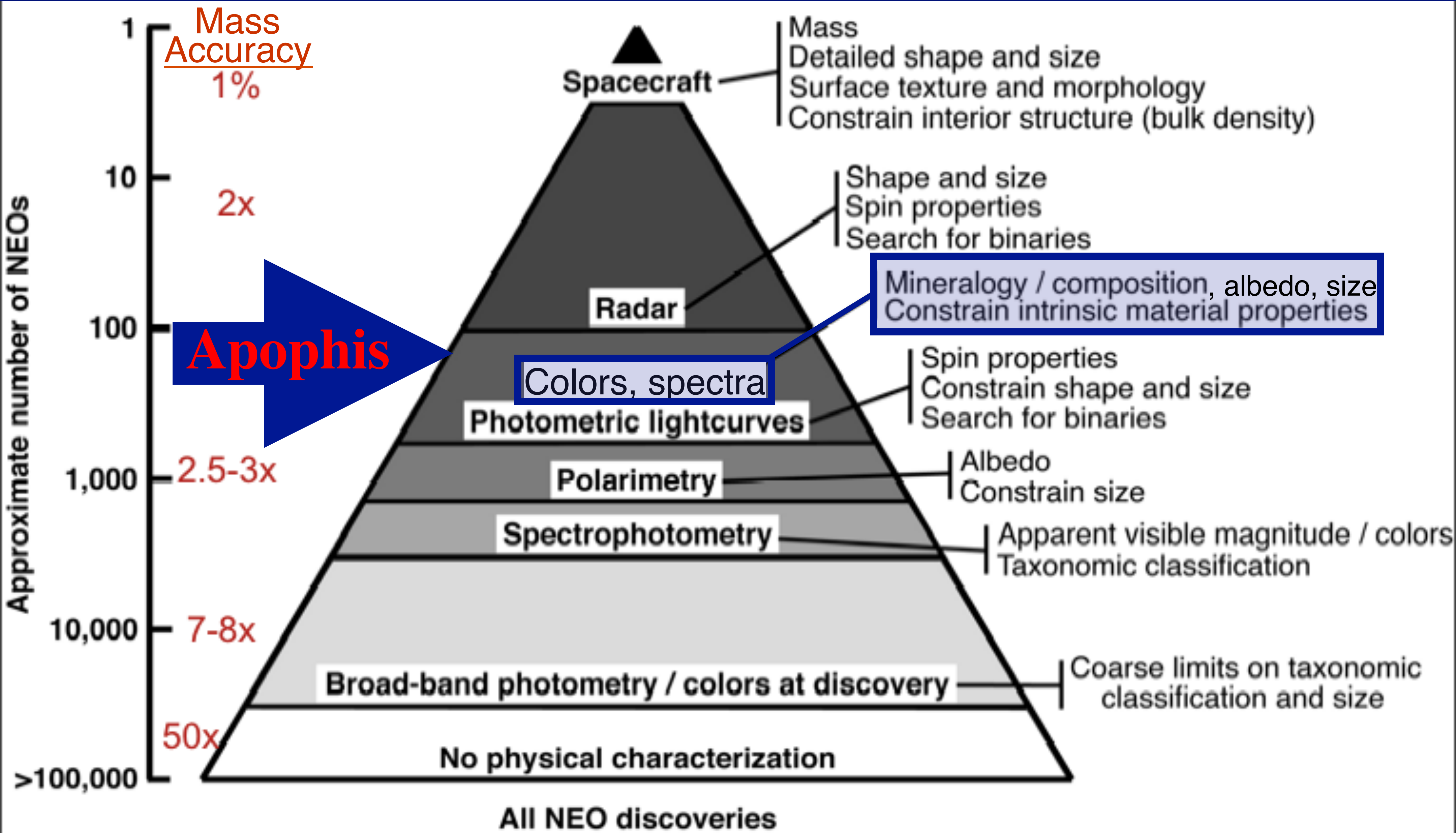
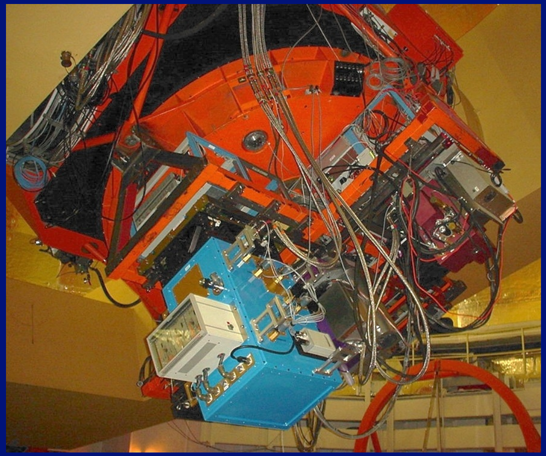
Current Status for Apophis

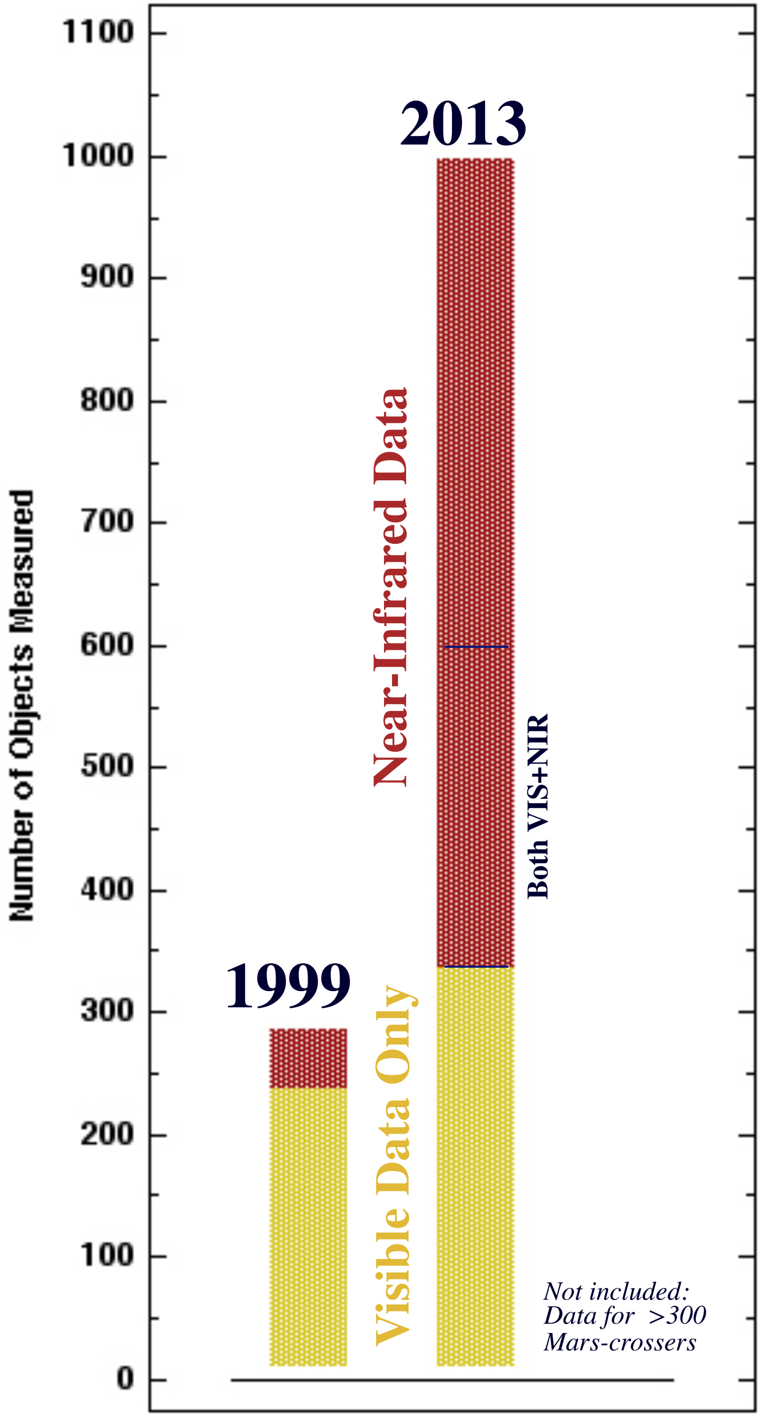


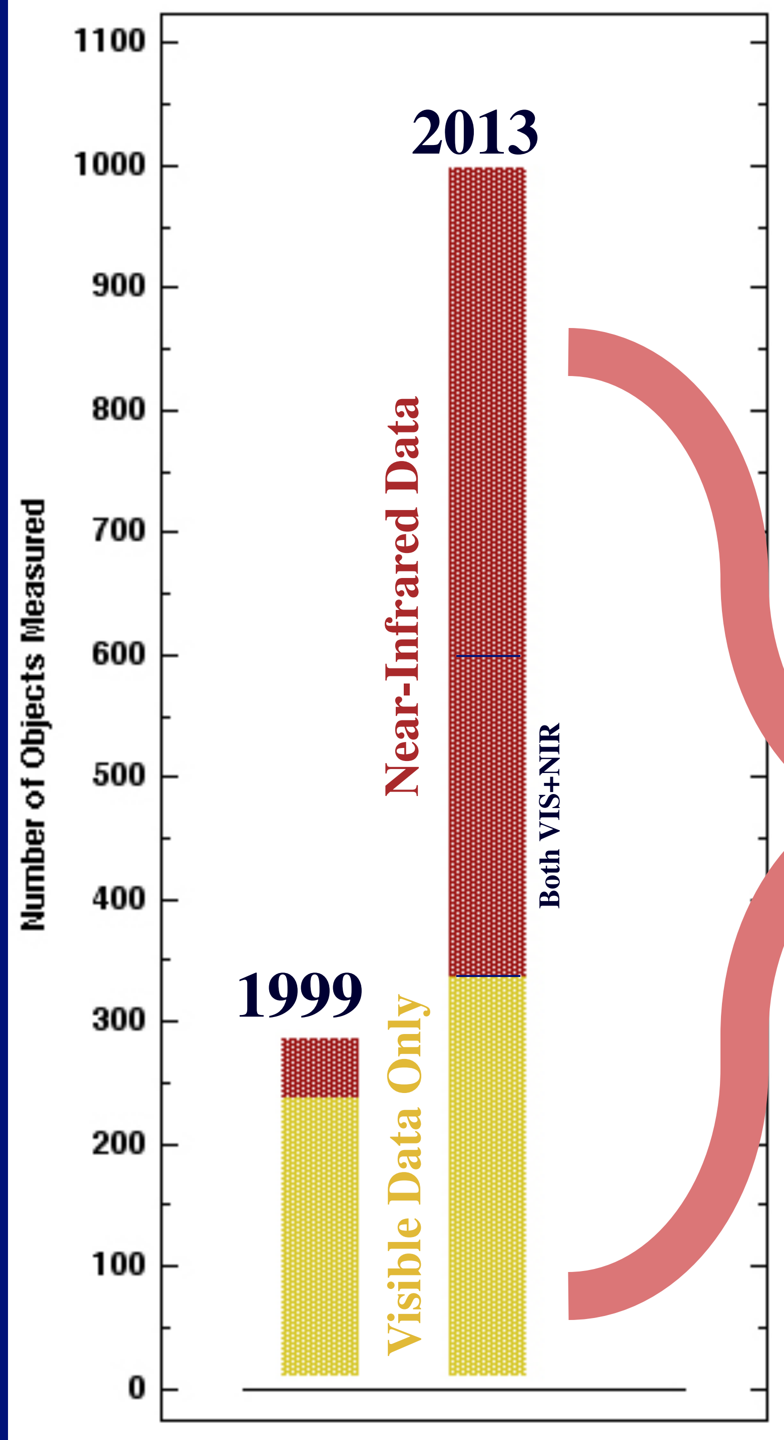
NEO Spectral Reconnaissance

- Visible data tally includes ECAS & SDSS.
- IRTF SpeX accounts for 85% of all NIR NEO data.



- Spectral reconnaissance for ~10% of total NEO population.





smass.mit.edu

Planetary Spectroscopy at MIT

Browse catalog of asteroid spectra

Browse Catalog of Asteroid Spectra

SMASS: Small Main-Belt Asteroid Spectroscopic Survey
The MIT-UH-IRTF Joint Campaign for NEO Spectral Reconnaissance

Please read below, "How to Use and Cite These Data" prior to proceeding.

MPC convention: off | on

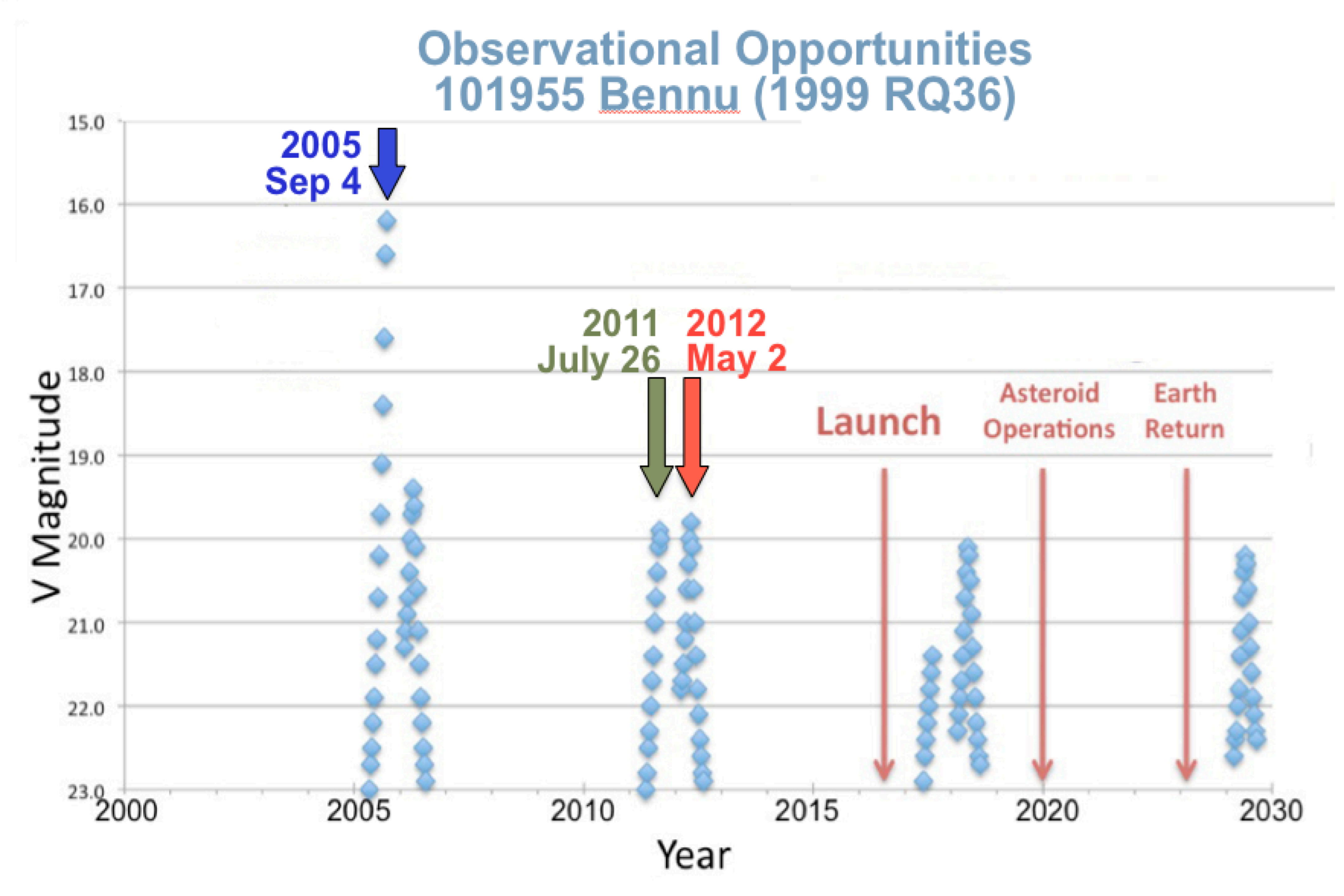
Number [sort]	Name [sort]	Provisional Designation [sort]	Data Available	Data Files	Data Reference [sort]	Last Updated [sort]
		2010 XZ_{67}	NIR		sp[128]	2014-01-06
		2011 BE_{38}	NIR		sp[098]	2011-05-12
		2011 EZ_{78}	NIR		sp[100]	2011-07-19
		2011 GA_{55}	NIR		sp[101]	2011-09-14
		2011 LJ_{19}	NIR		sp[102]	2011-10-24
		2011 OV_4	NIR		sp[101]	2011-09-14
		2011 PS	NIR		dm[003]	2011-09-21
		2011 PT_1	NIR		sp[102]	2011-10-24
		2011 SL_{102}	NIR		sp[105]	2012-03-09

Findings / Conclusions

- Physical measurements for hazard assessment are in parallel with NEO science goals.
- Physical observations are *required* as part of reliable hazard assessment. "*Know thy enemy*."
- **Apophis case study**: Spectral link to a specific well-studied meteorite group, provides the first line of defense for informing hazard assessment and mitigation.

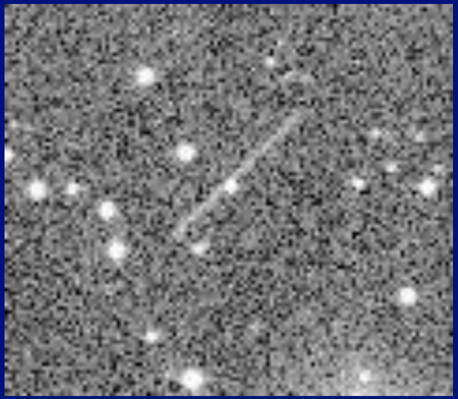
FIN

Back Up Slides



Observational Opportunities
101955 Bennu (1999 RQ36)
2005
Sep 4
2011
July 26
2012
May 2
Launch
Asteroid
Operations
Earth
Return
V Magnitude
15.0
16.0
17.0
18.0
19.0
20.0
21.0
22.0
23.0
2000
2005
2010
2015
2020
2030
Year

Size Determination



- Discovered object has brightness value m as measured by the detector.
- m is converted to standard V magnitude.
- V is converted to H magnitude by:

$$H = V - 5 \log (r\, \Delta) - \phi(\alpha)$$

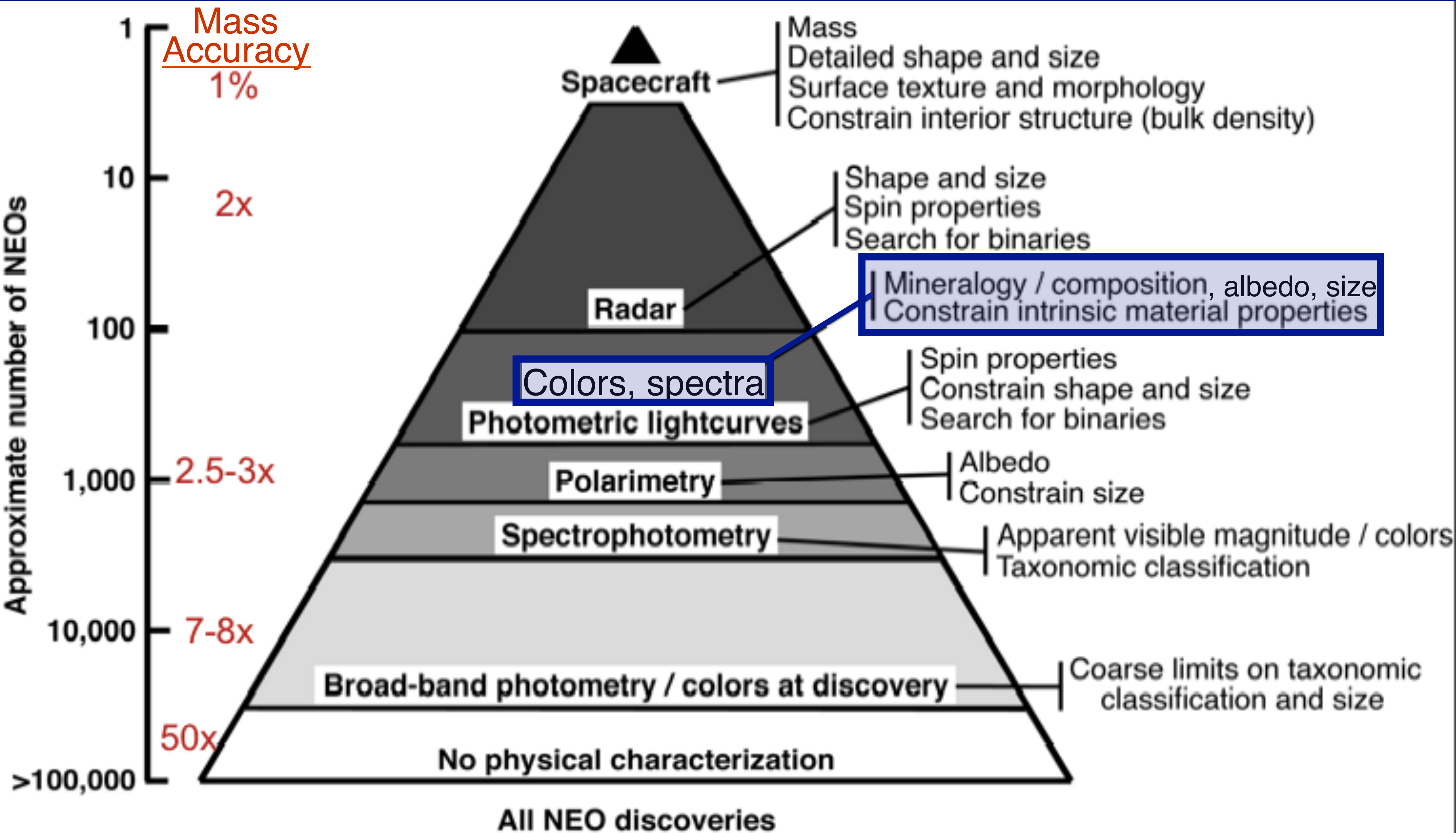
where r, Δ, α are determined by orbit.

- H is converted to diameter D by:

$$\log D = -0.5 \log(\rho) + 3.13 - 0.2H$$

where ρ is the albedo.

Characterization Pyramid



Case Study

Vol 458 | 26 March 2009 | doi:10.1038/nature07920 nature

The impact and recovery of asteroid 2008 TC_3

P. Jenniskens[1], M. H. Shaddad[2], D. Numan[2], S. Elsir[3], A. M. Kudoda[2], M. E. Zolensky[4], L. Le[4,5], G. A. Robinson[4,5], J. M. Friedrich[6,7], D. Rumble[8], A. Steele[8], S. R. Chesley[9], A. Fitzsimmons[10], S. Duddy[10], H. H. Hsieh[10], G. Ramsay[11], P. G. Brown[12], W. N. Edwards[12], E. Tagliaferri[13], M. B. Boslough[14], R. E. Spalding[14], R. Dantowitz[15], M. Kozubal[15], P. Pravec[16], J. Borovicka[16], Z. Charvat[17], J. Vaubaillon[18], J. Kuiper[19], J. Albers[1], J. L. Bishop[1], R. L. Mancinelli[1], S. A. Sandford[20], S. N. Milam[20], M. Nuevo[20] & S. P. Worden[20]

Figure 1 | Map of the Nubian Desert of northern Sudan with the ground-projected approach path of the asteroid and the location of the recovered meteorites. 2008 TC_3 moved from a geodetic longitude of 31.80381° E and latitude of +20.85787° N at 50 km altitude, to 32.58481° E, +20.70569° N at 20 km altitude above the WGS-84 ellipsoid. White arrow represents the path of the 2008 TC_3 fireball with the projected, non-decelerating ground path represented as a thin black line (altitude labels in km, within white ovals). The sizes of the red symbols indicate small (1–10 g), medium (10–100 g) and large (100–1,000 g) meteorites. Our dark-flight calculations show that 270-g fragments would have stopped ablating at around 32 km altitude, falling vertically on the ground at 30–60 m s^{-1}. Labels in white rectangles mark the position where meteorites of indicated masses are predicted to have fallen (calculations assume spheres released at 12.4 km s^{-1} from detonation at 37 km altitude, white star). In light yellow is shown the area that was systematically searched. Special attention was given to possible large fragments further down track, but none were found. Such larger masses would have carried residual forward velocity. The yellow line marks the path of the local train tracks with the location of Station 6 labelled.

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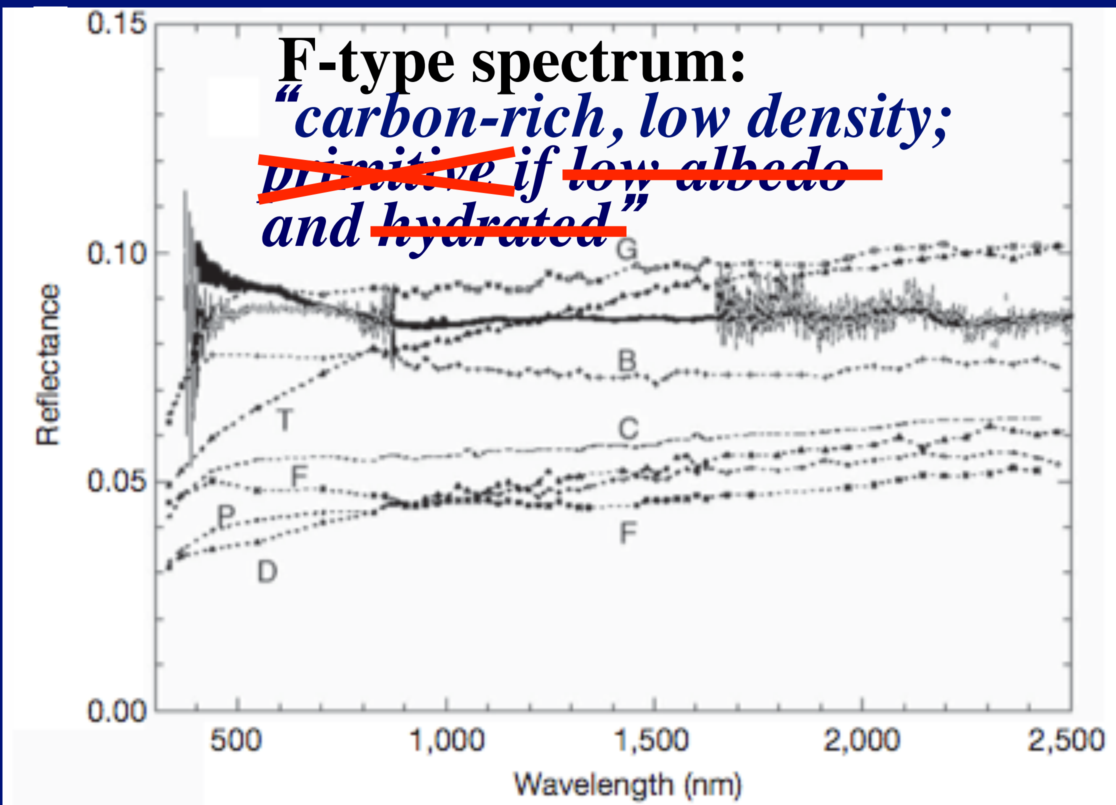
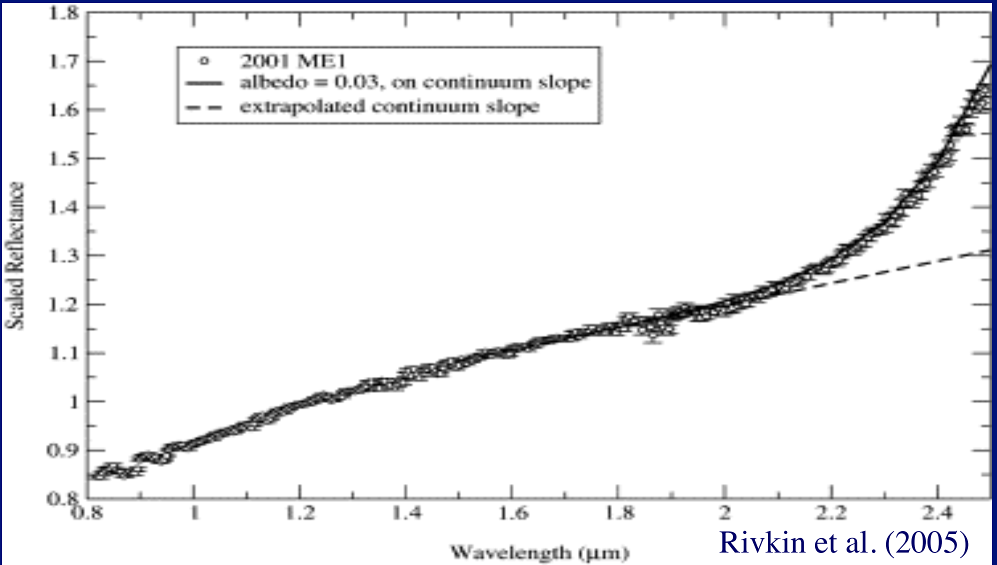


Figure 4 | Meteorite reflectance spectrum compared to that of asteroid 2008 TC_3.

"Carbon-rich, anomalous ureilite"

Direct Measurement of Low Albedo NEOs

- *Standard Thermal Model* (Lebofsky & Spencer 1989) shows low albedo asteroids in near-Earth space are warm enough to emit in the near-IR.
- First application using *IRTF SpeX* (2.5μm) to NEOs (1998 ST27) reported by Abell (ACM 2002; Thesis 2003).
- Model templates for application to NEOs by Rivkin et al. (2005).



Rivkin et al. (2005)

The Power of Reflectance Spectroscopy:
Mineral Analysis