FINAL REPORT FOR NASA GRANT NAG5-3939

RECONNAISSANCE OF NEAR-EARTH OBJECTS

Richard P. Binzel (MIT)
Principal Investigator

Summary: NASA sponsorship of asteroid research for this grant has resulted in 30 publications and major new results relating near-Earth asteroids to known meteorite groups, most especially ordinary chondrites. Analysis of observations continues.

Research Objectives

What are the relationships between asteroids, comets, and meteorites? All represent primordial samples from the early solar system, but how have their thermal, collisional, and dynamical evolution differed over the age of the solar system? Achieving such a fundamental understanding of the interrelationships of solar system small bodies has been a cornerstone for work in planetary science over the past three decades and continues to be of highest priority

Asteroids, comets, and meteorite source bodies all traverse near-Earth space and are therefore accessible to groundbased observations despite their typically small sizes. As has been demonstrated by nearly three decades of work, spectroscopic observations represent the most fundamental technique for measuring the physical properties of small solar system bodies. Over visible wavelengths, near-Earth objects observed to date have been found to display a wide range of distinctive spectral properties which appear to span the range between primitive (perhaps cometary) compositions to highly differentiated materials (likely formed in the asteroid belt). In addition, many apparent comet->asteroid transition objects (e.g. 4015 Wilson-Harrington) have been discovered and are in need of substantial follow-up physical study.

Thus, the study of near-Earth objects is key for achieving the fundamental science goals of understanding the relationships between asteroids, comets, and meteorites. A fundamental set of research objectives which must be met in order to achieve new advances is given below. This research program is being undertaken to accomplish each of these fundamental objectives:

- Characterize the compositional distribution of near-Earth objects (NEOs), most importantly size and orbital dependences within the distribution.
- Identify the population of NEOs that is most likely derived from comets.
- Identify the population of NEOs that is most likely derived from the asteroid belt.
- Identify NEOs that are potential analogs to known meteorite types.
- Identify and characterize NEOs as potential spacecraft mission targets.
- Identify and characterize NEOs having new and unusual spectral properties.
- Identify and characterize NEOs which may ultimately pose an impact hazard.

Year 1 Accomplishments: 1 October 1997 – 30 September 1998

Four observing runs using the MDM Observatory 2.4m Hiltner telescope and the Palomar 5m Hale telescope were accomplished. Measurements were achieved for more than 20 near-Earth objects, bringing the total for the Principal Investigator's current program to nearly 100 objects.

The sample size is now growing large enough to begin to address some of the fundamental relationships between asteroids, comets, and meteorites. One fundamental uncertainty in clarifying the big picture relationship between asteroids and meteorites has been the relationship between the most common asteroids (S-types) and the most common meteorites (ordinary chondrites). Historically, groundbased spectroscopic measurements have shown an apparent mismatch between these asteroid and meteorite types, thus leading to doubt and confusion for asteroid-meteorite interrelationships.

A new big picture has emerged as a result of this program involving spectroscopic sampling of a large number of near-Earth asteroids over a continuous range of sizes down to <1 km. About 10% of the smallest asteroids surveyed (~1 km in size) appear spectrally analogous to ordinary chondrite meteorites. Most importantly for clarifying the big picture, a continuous trend is found in the spectral properties which previously separated measurements of S-type asteroids and ordinary chondrite meteorites, where this trend is found to be continuous with respect to diameter.

We believe that groundbased spectroscopic measurements are now becoming extensive enough to remove the confusion over the relationship between S-asteroids and ordinary chondrite meteorites. Ordinary chondrites are derived from within the S-asteroid population. Spectroscopically, ordinary chondrites are an end-member of the S-asteroid population, where the size-dependent relationship is the result of collisional processing of the surface, regolith retention, or time-dependent surface evolution. Most specifically, the continuous relationship argues against ordinary chondrite meteorites being derived from a separate sample of small solar system bodies.

We are also pursuing the identification of unusual mineralogical features within the spectra of near-Earth asteroids. We have identified a strong UV feature within the spectrum of 3103 Eger to be due to troilite (FeS) which has implications for a strong early heating history for this class (E class) of asteroids. Analysis and publication are in progress.

Year 2 Accomplishments: 1 October 1998 – 30 September 1999

Five observing runs using the Kitt Peak 4.0m telescope and the Palomar 5m telescope were accomplished. Measurements were achieved for more than 70 near-Earth objects, bringing the total for the Principal Investigator's current program to more than 150 objects. Our observations have included (9969) Braille, showing from groundbased telescopes the likelihood of its V-type spectrum. Our observations of the MUSES-C target asteroid, (10302) 1989 ML show that its neutral spectrum may be indicative of a composition resembling shock-darkened ordinary chondrite meteorites.

The total sample size is now growing large enough to begin to address some of the fundamental relationships between asteroids, comets, and meteorites. These results were summarized in my invited review talk at the *Asteroids Comets Meteors* meeting held in Ithaca, New York in July. The highlights include:

- About 10% of the measured NEOs have spectra resembling ordinary chondrite meteorites, the class that represents about 80% of falls.
- There appears to be a definitive relationship between S-asteroids and ordinary chondrites, where their spectral properties vary continuously between these two classes.
- There is a size dependence to asteroid spectral properties, where smaller asteroids may be interpreted as having "fresher" and less weathered surfaces.

Year 3 Accomplishments: 1 October 1999 – 30 September 2000

Our strategy for achieving substantial progress in the scientific understanding of NEOs continued by completing six observing runs at KPNO and Palomar Observatories and by beginning a program of thermal flux measurements (to determine albedos) at the Keck Observatory. For each night of telescope time, our targets were chosen in the priority of:

1) The smallest diameter NEOs accessible within the telescope magnitude limit.
2) Newly discovered NEOs.
3) Previously known NEOs or other asteroids / comets identified as mission targets.
4) Mars crossing asteroids.
5) Small main-belt asteroids near the 3:1 and ν_6 resonances.

During Year 3, the total number of NEOs observed by this program surpassed 200.

Our scientific strategy for concentrating on visible wavelength spectroscopy measurements is that this technique allows us the greatest potential to push the limits of technology and telescope aperture to sample the compositional properties of the smallest (and usually faintest) available objects. By achieving measurements of the smallest available objects, we have worked to sample the greatest diversity of objects spanning a wide diameter range where smaller (and usually fainter) objects provide the greatest scientific and observational challenge.

Newly discovered NEOs have been pursued because it is often the case that the subsequent viewing geometry for new objects (and most especially small objects that are only visible very near the Earth) makes them virtually "unobservable" for decades following their discovery apparition. Thus frequent access to the telescope is *critically* important for near-Earth object reconnaissance.

Analysis work has continued with major meeting presentations and publications, as listed. A principal conclusion of this first stage analysis is the insight into the relationship between the most common asteroids (S-types) and ordinary chondrite meteorites.

No Cost Extension Period: 1 October 2000 – 31 December 2001

During this period of limited funds, observing runs became limited to four in number with most effort concentrating on bringing existing papers to publication. In addition, specific effort was devoted to understanding the detailed nature of individual targets identified for spacecraft exploration.

An example in particular is our analysis of the (now current) MUSES-C spacecraft target 1998 SF36. Our observations show this asteroid to have spectral features that are nearly identical to those of ordinary chondrite meteorites, yet the spectrum is offset by a constant red slope. New results from the laboratory regarding the effects of nano-phase iron in the reflectance spectra of asteroids have been incorporated into our work. We find that we can achieve an excellent match between the spectrum of 1998 SF36 and ordinary chondrite meteorites if we postulate the asteroid spectrum is reddened by about 0.01% nanophase iron.

Finally, as a prerequisite to the ongoing analysis of the global properties of the NEO population, we have finalized the form for a new taxonomic classification system that takes advantage of the wealth of information within CCD spectra. These results were completed and submitted during this final year.

Summary Publication List

Papers in Refereed Journals (Total 13)

Binzel, R. P.
"Meteorites on the Fast Track." *Meteoritics & Plan. Sci.* **33**, 955, 1998.

Binzel, R. P.
"The Torino Impac Hazard Scale." *Plan. Space Sci.* **48**, 297-303, 2000.

Lazzaro, D., Michtenko, T , Carvano, J. M., Binzel, R. P., Bus, S. J, Burbine T. H.,
Mothe-Dinez, T., Florczak, M,, Angeli, C. A., and Harris, A. W.
"Discovery of a Basaltic Asteroid in the Outer Main Belt."
Science **288**, 2033-2035, 2000.

Binzel, R. P.
"Asteroids Come of Age." *Science* **289**, 2065-2066, 2000.

Binzel, R. P. "Asteroid Science: Two Centuries Young."
Meteoritics & Plan. Sci. **36**, 327-328, 2001.

Burbine, T. H., Binzel, R. P., Bus, S. J., and Clark, B. E.
"K Asteroids and CO3/CV Chondrites." *Meteoritics & Plan. Sci.* **36**, 245-253, 2001.

Binzel, R. P., Harris, A. W., Bus, S. J., and Burbine, T. H.
"Spectral Properties of Near-Earth Objects: Palomar and IRTF Results for 48 Objects Including Spacecraft Targets (9969) Braille and (10302) 1989 ML."
Icarus **151**, 139-149, 2001.

Binzel, R. P. (2001).
"Forging the Fourth Link Between Planetary Worlds:
Vesta and the HEDS." *Meteoritics & Plan. Sci.* **36**, 479-480, 2001.

Burbine, T. H., Buchanan, P. C., Binzel, R. P., Bus, S. J., Hiroi, T., Hinrichs, J. L.,
Meibom, A., and McCoy, T. J.
"Vesta, Vestoids, and the Howardite, Eucrite, Diogenite Group:
Relationships and the Origin of Spectral Differences."
Meteoritics & Plan. Sci. **36** 761-781, 2001.

Binzel, R. P., Bus, S. J., Sunshine, J., and Burbine, T.
"MUSES-C Target Asteroid 1998 SF36: A Reddened Ordinary Chondrite."
Meteoritics & Plan. Sci. **36**, 1167-1172, 2001.

Harris, A. W., Delbo, M., Binzel, R. P., Davies, J. K., Roberts, J., Tholen, D. J., and Whiteley, R. J.
"Visible to Thermal Infrared Spectrophotometry of a Possible Inactive
Cometary Nucleus " *Icarus* **153**, 332-337, 2001.

Bus, S. J., and Binzel, R. P.
"Phase II of the Small Main-Belt Asteroid Spectroscopic Survey: The
Observations." In press, *Icarus.*

Bus, S. J., and Binzel, R. P.
"Phase II of the Small Main-Belt Asteroid Spectroscopic Survey: A Feature-
Based Taxonomy." In press, *Icarus.*

Other Publications (Total 17)

Binzel, R. P., Bus, S. J. and Burbine, T. H.
"Size Dependence of Asteroid Spectral Properties: SMASS Results for Near-Earth and Main-Belt Asteroids." LPSC XXIX, Abstract #1222, Lunar and Planetary Institute, Houston (CD-ROM), 1998.

Sunshine, J. M., Binzel, R. P., Burbine, T. H., and Bus, S. J.
"Is Asteroid 289 Nenetta Compositionally Analogous to the Brachinite Meteorites?"
LPSC XXIX, Abstract #1430, Lunar and Planetary Institute, Houston (CD-ROM), 1998.

Binzel, R. P., Bus, S. J., and Burbine, T. H.
"Relating S-Asteroids and Ordinary Chondrite Meteorites: The New Big Picture."
BAAS **30**, 1041, 1998.

Bus, S. J., Binzel, R. P., and Burbine, T. H.
"A Feature-based Taxonomy Derived from 1190 SMASSII CCD Spectra."
BAAS **30**, in 1025, 1998.

Binzel, R. P., Bus, S. J., Burbine, T. H.
"The Orbital Distribution of Vesta-Like Asteroids." In *Lunar and Planetary Science XXX*, Abstract #1216, Lunar and Planetary Institute, Houston (CD-ROM), 1999.

Veverka, J., Ahrens, T., Belton, M., Binzel, R. P., Boynton, W., Feldman, P., Yelle, R.
"Exploring Comets, Asteroids, and Related Bodies." In *Lunar and Planetary Science XXX*, Abstract #1739, Lunar and Planetary Institute, Houston (CD-ROM), 1999.

Binzel, R. P., Bus, S. J., Burbine, T. H.
"The Compositional Distribution of the Near-Earth Asteroid Population."
Asteroid Comets Meteors '99 Abstracts, p. 21, 1999.

Hinrichs, J. L., Lucey, P. G., Meibom, A., Burbine, T. H., Binzel, R. P., Krot, A. N.
"Temperature Dependent Spectra of Meteorites: Asteroid Implications."
Asteroid Comets Meteors '99 Abstracts, p. 101, 1999.

Binzel, R. P., Barucci, M. A., and Fulchignoni, M.
"The Origin of the Asteroids."
In *Scientific American's Book of the Cosmos*, New York, 1999.

Binzel, R. P. "1999 LD31" *IAUC* 7376, 2000.

Binzel, R. P. (2000). "Assessing the Hazard: The Development of the Torino Scale."
The Planetary Report **19**, 6-10.

Binzel, R. P., Bus, S. J. Burbine, T. H., Stuart, S. (2000).
"Size and Orbital Dependent Properties of Near-Earth Objects." *BAAS* **32**, 1000.

Delbo, M., Harris, A. W., Binzel, R. P., and Davies, J. K. (2000).
"Physical Characterization of Near-Earth Objects With the Keck Telescope."
BAAS **32**, 1000.

Bus, S. J. and Binzel, R. P. (2000).
"A Neural Network Simulation of the SMASS II Asteroid Taxonomy." *BAAS* **32**, 1004.

Other Publications (continued)

Binzel, R. P., Bus, S. J., Burbine, T. H., Rivkin, A. S. (2001).
"Announcing the Availability of the MIT SMASS and SMASSIR Data Sets."
Lunar Plan. Sci. **XXXII**, (CD-ROM).

Binzel, R. P., Rivkin, A S., Bus, S. J., Sunshine, J. M., and Burbine, T.H. (2001).
"MUSES-C Target Asteroid 1998 SF36: A Reddened Ordinary Chondrite." *Meteoritics & Planetary Science (Supplement)* **36**, A20-21.

Burbine, T. H., McCoy, T. J., Binzel, R. P. and Bus, S. J. (2001).
"Spectra of Aubrites and Their Constituent Minerals."
Meteoritics & Planetary Science (Supplement) **36**, A31-32.

Bus, S. J., Sunshine, J. M., Binzel, R. P., and Burbine, T.H. (2001). Investigating the Spectral Continuum Between A-type and S-type Asteroids. *Meteoritics & Planetary Science (Supplement)* **36**, A20-21.