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Spectral properties and composition of potentially hazardous Asteroid (99942) Apophis

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ABSTRACT

The known close approach of Asteroid (99942) Apophis in April 2029 provides the opportunity for the case study of a potentially hazardous asteroid in advance of its encounter. The visible to near-infrared (0.55 to 2.45 μm) reflectance spectrum of Apophis is compared and modeled with respect to the spectral and mineralogical characteristics of likely meteorite analogs. Apophis is found to be an Sq-class asteroid that most closely resembles LL ordinary chondrite meteorites in terms of spectral characteristics and interpreted olivine and pyroxene abundances, although we cannot rule out some degree of partial melting. A meteorite analog allows some estimates and conjectures of Apophis' possible range of physical properties such as the grain density and micro-porosity of its constituent material. Composition and size similarities of Apophis with (25143) Itokawa suggest a total porosity of 40% as a "current best guess" for Apophis. Applying these parameters to Apophis yields a mass estimate of 2×10^{10} kg with a corresponding energy estimate of 375 Mt for its potential hazard. Substantial unknowns, most notably the total porosity, allow uncertainties in these mass and energy estimates to be as large as factors of two or three.

1. Introduction

Among currently known asteroids capable of making close approaches to the Earth, (99942) Apophis is perhaps the most renowned. MacRobert (2005) provides an account of Apophis' discovery and early hazard assessment. Its predicted close approach to the Earth on (Friday) April 13, 2029 at a geocentric distance of 5.98 ± 0.26 Earth radii (Chesley, 2005) and current 1:43000 impact probability in 2036 (NASA JPL Sentry; September 2008) make Apophis an important case study for discerning the physical characteristics of objects that may pose an Earth impact hazard.

Here we report groundbased visible and near-infrared spectroscopic observations of Apophis. Our initial purpose in obtaining spectral measurements was to determine the taxonomic class of Apophis in order to constrain its size during the earliest stages of its hazard assessment. (Upon discovery, the H magnitude of an asteroid gives a very limited constraint on the size because of the lack of knowledge of its albedo.) The size can be constrained through demonstrated correlations between taxonomic classes and albedos for near-Earth objects (e.g., Delbo et al., 2003). A more in depth analysis of the spectral properties allows some mineralogical interpretation and possible meteorite analogs to be considered. In the latter case, inferences can be offered on the likely physical nature of the asteroid. Such inferences can provide detailed information for the purpose of evaluating potential impact consequences and planning possible mitigation strategies.

The following sections describe our observations, their analysis to constrain the size of Apophis, and an interpretation of Apophis' possible composition and meteorite analog. As a conclusion, we consider the implications of these results in terms of the constraints they place on our estimates of outcomes for Apophis as

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a potentially hazardous asteroid (PHA). Thus Apophis can serve as an illustration of our ability to use groundbased data as input for assessing the nature and implications of newly discovered potentially hazardous asteroids.

2. Observations

We obtained 0.55–2.45 μm spectral measurements of Apophis using the 6.5 m Baade Telescope at the Magellan Observatory (Las Campanas, Chile) and using the 3 m NASA Infrared Telescope Facility (IRTF) located on Mauna Kea, Hawaii. The IRTF measurements were obtained first, on 2005 January 8 (05:30–06:30 UT; airmass 1.2) during Apophis' most favorable apparition (V magnitude 17.4) until 2013. These IRTF measurements were obtained as part of a regularly scheduled routine program of near-Earth object characterization conducted jointly between the IRTF, University of Hawaii, and MIT. These observations occurred very shortly after the public recognition of Apophis' potential hazard (MacRobert, 2005) and thus Apophis received high priority as a program target. We utilized the instrument SpeX (Rayner et al., 2003) to obtain measurements covering the wavelength range 0.8–2.45 μm over a total integration time of 3000 seconds. Our observing and reduction procedures are described by Rivkin et al. (2004). We transformed our measurements to a solar reflectance spectrum utilizing Hyades 64 as our solar analog star. Results from a preliminary reduction of our data were presented by Binzel et al. (2005). For the final result presented here, we utilized 14 out of the 24 total exposures, selecting the exposures giving the highest peak signal-to-noise in the raw images. Our final reduction also more strictly rejects low signal-to-noise portions of the telluric water bands and extends only to 2.45 μm. We discuss the range of variation for this processing, relative to the preliminary reduction, in Section 3.

Our immediate reduction of these 8 January 2005 observations (Binzel et al., 2005) showed Apophis to have spectral properties placing it in the Sq- to Q-type range of asteroid taxonomy, typical for most near-Earth objects. Using the survey statistics for Sq- and Q-type NEO albedos from Delbo et al. (2003) and from Stuart and Binzel (2004), we determined 0.35 as an "initial best estimate" for the albedo of Apophis. Our initial reductions, as well as our later reductions, also showed no evidence for significant thermal flux (upper limit 2.5% at 2.5 μm), a null result consistent with the 0.35 albedo estimate. Thus with the acquisition of this single set of spectral measurements in January 2005 we were able to deduce an estimated diameter of 300 m for Apophis, based on the then reported H magnitude of 19.3. This 300 m size served as the "best available guess" for all Apophis hazard assessments until the subsequent results from substantially more detailed work performed by Delbo et al. (2007). We further address the size estimates for Apophis in Section 3.

To complement our near-infrared spectrum and aid in our modeling efforts to deduce the composition of Apophis, we obtained visible (0.55–0.90 μm) spectral measurements using the Inamori Magellan Areal Camera and Spectrograph (IMACS; Dressler et al., 2006) on the 6.5 m Baade Telescope at the Magellan Observatory (Las Campanas, Chile). We used IMACS in the "long camera" ($f/4$) mode with a 300 line/mm grating blazed at 0.65 μm. The observations, totaling 1200 seconds of integration time were obtained near the meridian on 22 February 2006 (UT 08:40–09:20; airmass 1.0) under good (<1 arcsecond) seeing conditions using a 1.5 arcsecond slit. Apophis had a predicted apparent V magnitude near 19.6 at the time of the observations. We reduced the Magellan observations to solar reflectance using near simultaneous measurements of the nearby solar analog star Landolt 107–998 (airmass 1.1), using the same procedures described in Binzel et al. (2004).

Our final reflectance spectrum of Apophis is shown in Fig. 1a, where we normalize the spectrum to unity at 0.55 μm and use the 0.8- to 0.9-μm overlap region to scale the near-infrared portion of the spectrum with the visible.

Table 1
Composition of (99942) Apophis estimated using the Shkuratov et al. (1999) model. (Model fit displayed in Fig. 1c.) Apophis results are compared with the average compositions (in vol%) measured in the laboratory for H, L and LL ordinary chondrite meteorites (Hutchison, 2004). Apophis resides within the range of LL chondrites.

Object	Olivine (%)	Ortho-pyroxene (%)	Clino-pyroxene (%)	Mg-number
H	53	39	8	80–85
L	61.5	30.5	8	74–80
Apophis	65–75	17–27	3–13	65–75
LL	72.5	20	7.5	68–78

3. Interpretations

We model and interpret the spectrum of Apophis using a variety of techniques with the goal of a basic interpretation for its composition. We find (Fig. 1b) that Apophis appears well classified as an Sq-type, using the categories of the Bus (1999) taxonomy, extended to the near-infrared by DeMeo (2007) and DeMeo et al. (2009). (The initial reduction presented by Binzel et al. (2005), with lower signal-to-noise gave an ambiguous classification between Sq- and Q-type.) As noted in Section 1, NEO albedo measurements and survey statistics from Delbo et al. (2003) and Stuart and Binzel (2004) yield an interpreted albedo for this taxonomic class of 0.35 and an estimated diameter of 300 m. Delbo et al. (2007) report direct measurements of the albedo as 0.33 ± 0.08 along with an updated H magnitude value of 19.7 ± 0.4. Combining these, Delbo et al. provide the current best diameter estimate of Apophis as 270 ± 60 m.

The Sq-type spectrum of Apophis displays a broadened 1-μm band and the presence of a 2-μm band, similar to the spectral characteristics for pyroxene + olivine assemblages found in ordinary chondrite meteorites. To quantify the mineralogic interpretation, we modelled Apophis' spectrum using the Shkuratov scattering model (Shkuratov et al., 1999). The first step of the modelling consisted of choosing reasonable end member minerals. For these we chose to use the optical constants of the main end member minerals found in ordinary chondrites, namely olivine, orthopyroxene, and clinopyroxene. For these mineral constituents, we considered the optical constants for different chemistries, i.e., different Mg-numbers from Lucey (1998). The free parameters of the mineralogy model are the relative abundance of the components (whose sum must be equal to 1), the mineral chemistries (Mg-number) of the various components, and the effective optical path length for the reflected photons (physically, a function of the grain size; Shkuratov et al., 1999).

To find the best fit of the model spectrum to the data, we used a Levenberg–Marquardt algorithm within IDL to determine the minimum root-mean-squared (RMS) residual. Fig. 1c shows the result: The spectrum of Apophis is modelled by a mixture consisting of 65–75% olivine (Ol), 17–27% orthopyroxene (Opx), and 3–13% clinopyroxene (Cpx). (Formally the best fit occurs for 70% Ol, 22% Opx, and 8% Cpx with a ±5% one-sigma uncertainty for each. Fig. 1c shows the model to be within one-sigma of the data at every wavelength.) Within this model fit, we find an Mg-number equal to 70 (uncertainty ±5) and a grain-size parameter of 6.1 (uncertainty ±0.3). To achieve this model solution, it was also necessary to account for the overall red slope of Apophis' spectrum. (Within our mineralogic model there is otherwise no variation in composition or optical path length that can reproduce the spectral reddening observed in the visible and near-infrared wavelength range.) For this slope correction, we utilized the space weathering model of Brunetto et al. (2006) where the best fit (performed

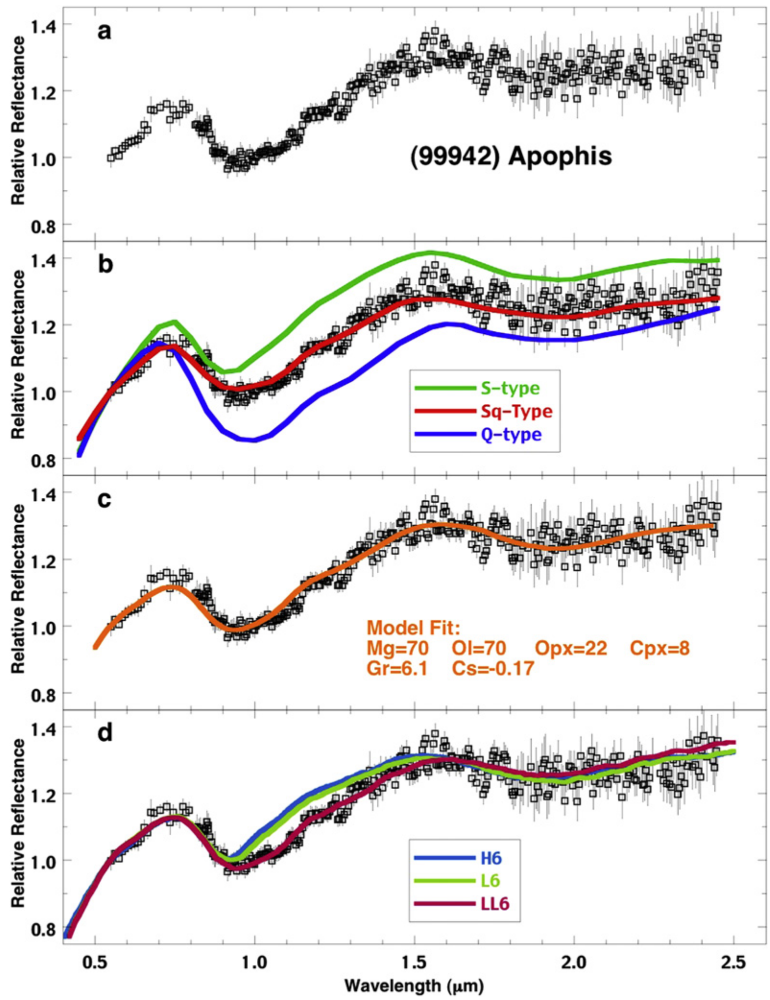

Fig. 1. (a) Combined visible plus near-infrared reflectance spectrum of Asteroid (99942) Apophis, normalized to unity at 0.55 µm obtained using the Magellan 6.5 m and IRTF 3 m telescopes. (b) Comparison among asteroid taxonomy classes showing our conclusion for assignment of Apophis as a member of the Sq-class. (c) Mineralogic model fit to Apophis using the model method described by Shkuratov et al. (1999). The model constituents considered are olivine (Ol), orthopyroxene (Opx), and clinopyroxene (Cpx). The best fit model result is plotted, where the Ol, Opx, and Cpx parameters each have estimated uncertainties of ±5%. (Analysis of these model fit parameters is presented in Table 1.) Additional free parameters in the model (see Section 3 for details) are Mg-number (Mg), grain size parameter (Gr), and a space weathering slope parameter (Cs) from the model of Brunetto et al. (2006). (d) Comparison between the reflectance spectrum of Apophis and laboratory reflectance spectra of the major meteorite groupings of ordinary chondrites, reddened using the model of Brunetto et al. (2006) to match the slope of Apophis. We find the best qualitative match is for LL ordinary chondrites. (Meteorite laboratory spectra are from RELAB.)

as an integral part of the overall minimum RMS solution) yielded a Cs value of -0.17 ± 0.01. The recognition of space weathering as a process that affects spectral slope has a long history (Clark et al., 2002) and is also recognized by *in situ* spacecraft as being present on comparably small near-Earth objects such as (25143) Itokawa (Hiroi et al., 2006).

In Table 1, we compare these mineral model parameters to laboratory measurements of ordinary chondrite meteorites. Within the model uncertainties, within the uncertainties of our asteroid measurements, and within the limitations of considering only three mineral constituents, we find the following result for Apophis: a relatively high olivine abundance and low orthopyroxene abundance, as well as the low Mg-number correlate most closely with the LL chondrite meteorite group. Thus Apophis is found to be typical among the majority of PHAs; Vernazza et al. (2008) find that ∼2/3 of all PHAs have spectral properties and interpreted mineralogies comparable to LL chondrite meteorites.

Beyond our mineralogic modelling and comparison with meteorite chemistries, we can also directly compare the spectrum of Apophis with laboratory measurements of meteorite reflectances. For this comparison, we utilize meteorite spectra from the Reflectance Experiment Laboratory (RELAB) database. We present the results in Fig. 1d. For each meteorite spectrum we applied the same space weathering model (Brunetto et al., 2006) to achieve the best fit to the asteroid spectral slope. We find this direct comparison yields the most reasonable match between major meteorite groups and Apophis to be with respect to an average for LL6 ordinary chondrite meteorites. Most important to this match is that it satisfies the characteristics of the broad 1 µm band as well as the shallow 2 µm band. The resulting best matches for averages of each meteorite type are shown in Fig. 1d. Within Fig. 1d it is seen that while the H and L ordinary chondrite meteorites are able to match the 2 µm band, neither H nor L chondrites are able to fit the width of the broad 1 µm band. Our mineralogy model attributes this broader 1 µm band to an abundance of olivine. Applying our preliminary reduction (Binzel et al., 2005; lower signal-to-noise overall and inclusion of nearly all channels in the telluric bands), or alternatively eliminating all data points at telluric water bands, yields no fundamental change; the spectrum of Apophis shows a broad 1 µm band and a shallow 2 µm band, yielding the same interpreted result.

A quantitative comparison of reflectance spectral properties between Apophis and potential meteorite analogs is displayed in Fig. 2. By quantifying and comparing spectral properties directly,

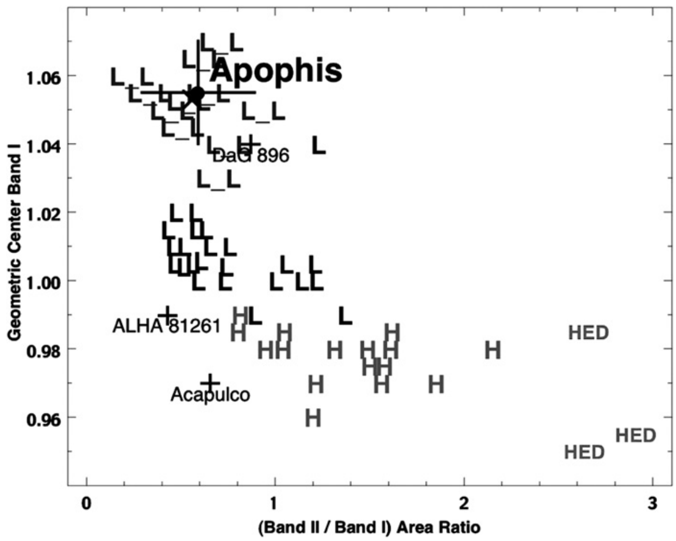

Fig. 2. Empirical modeling results for the spectral parameters of Apophis compared with a statistical sampling of H, L, and LL ordinary chondrite meteorites, as well as with the highly differentiated class of HED meteorites and partially melted achondrites. These purely empirical (no underlying mineralogy assumptions) measurements of the geometric band center and ratio of the spectral band areas (defined in Section 3 of the text) place Apophis in the same field as the LL ordinary chondrite meteorites. Our error bar for Apophis takes into account various approaches to the processing of our spectral data, such as performed by Binzel et al. (2005), as described in the text. Apophis plots almost identically with (25143) Itokawa (large X), predominantly interpreted as an LL chondrite based on groundbased and spacecraft data (Binzel et al., 2001; Abe et al., 2006; Okada et al., 2006). Partially melted achondrites (+ symbols with labels) are also shown, where the similarity in plotted location of DaG 896 leaves open the possibility for some degree of partial melting in the interpreted meteorite analog for Apophis.

we perform an analysis that is independent of mineralogical assumptions. To quantify the parameters of each spectrum, we measure the geometric center of the 1-µm band and the area of each band. For Fig. 2, we utilize the Modified Gaussian Method (MGM) of Sunshine and Pieters (1993) as a mathematical tool for measuring these band parameters. (We do not attempt any mineralogic interpretation of the MGM output.) Within MGM, we set the continuum to be linear in wave number space, i.e. proportional to $1/\lambda$. We mathematically define the "geometric center" of the band as the wavelength at which a vertical line bisects the calculated area of the band exactly in half. There are numerous other approaches for fitting bands and band centers (e.g., Gaffey et al., 1993), where each method yields its own internally consistent set of values. We utilize our values in an internally consistent way by applying our spectral band fitting procedures identically to both asteroids and meteorites. Fig. 2 compares the band parameters for Apophis relative to those for RELAB spectra of H, L, and LL chondrites. Within Fig. 2, we plot on the horizontal axis our calculated ratio of the Band II (2-µm band) area relative to the Band I (1-µm band) area. The independent method results of Fig. 2 show that the spectral characteristics of Apophis reside well within the field of the LL chondrite meteorites. Uncertainties arising from multiple alternatives within spectral processing of telescopic data are included in our error analysis (see Fig. 2 caption). In this analysis we also include a comparison to the highly differentiated HED meteorites, showing clearly that Apophis has spectral characteristics substantially different than the HED meteorite class. Additionally, Fig. 2 includes RELAB spectra for partially melted achondrites Acapulco (McCoy et al., 1992), ALH 81261 (Zipfel and Palme, 1993), and Dar al Gani (DaG) 896 (Folco et al., 2002). Of these, only DaG 896 falls effectively within one-sigma of Apophis, as noted below.

While the mineralogic modelling and empirical comparisons to meteorites we have presented here are all most consistent with

Table 2
Range of physical parameters for (99942) Apophis and corresponding mass and kinetic energy estimates. Results are based on LL chondrite meteorites and *in situ* measurements for Asteroid (25143) Itokawa, comparable in size and composition with Apophis. Our favored interpretation is shown in **bold**.

Parameter	Min	Avg	Max	Reference
Apophis diameter (m)	210	270	330	Delbo et al. (2007)
Grain density (g/cm^3)	3.4	3.5	3.6	Britt and Consolmagno (2003)[a]
Bulk density (g/cm^3)	3.0	3.2	3.4	Britt and Consolmagno (2003)[a]
Micro-porosity (%)	3.7	7.9	12.1	Britt and Consolmagno (2003)[a]
Macro-porosity (%)	0	20	50	Britt et al. (2002)

Calculations for Apophis

Parameter	Min	Avg	Max	Itokawa-like
1 − total porosity (micro + macro)	0.38	0.72	0.96	**0.60**[b]
Mass ($\times 10^{10}$ kg)	0.7	2.4	6.1	**2.0**[c]
Kinetic energy[d] (Mt TNT)	105	450	1100	**375**

[a] Values used here as "Max" and "Min" are their mean + and − one standard deviation from their Table 4.
[b] Total porosity of 40% from Abe et al. (2006).
[c] For Apophis 270 m diameter, 3.2 g/cm^3 bulk density.
[d] For impact velocity 12.6 km/s (Chesley, 2005).

the conclusion that Apophis shows a close comparison to LL ordinary chondrites, we cannot be certain this solution is unique. For example, Apophis has similar spectral characteristics to (25143) Itokawa, the target for the Hayabusa spacecraft mission. (Itokawa falls at an almost identical location as Apophis in Fig. 2.) While Binzel et al. (2001) concluded by modelling ground based spectra that Itokawa is most likely an LL chondrite, modelling of similarly obtained Itokawa spectra by Abell et al. (2007) also allows the possibility that Itokawa may be represented by an LL chondrite mineralogy that has been subjected to partial melting. Overall the *in situ* measurements by the Hayabusa spacecraft yield a preference for a direct correspondence to LL chondrites, but they do not entirely rule out the case for partial melting (Abe et al., 2006; Okada et al., 2006). Similarly, we do not rule out the possibility of partial melting of Apophis as illustrated by the plotted location of DaG 896 within Fig. 2, a meteorite interpreted to be represent the silicate fraction of a partially melted and rapidly cooled H chondrite (Folco et al., 2002).

4. Conclusions

A meteorite analog interpretation for Asteroid (99942) Apophis allows a direct assessment of its potential impact hazard. While the odds against impact are comfortably in our favor (at present 43000 to 1 likelihood of no impact), it is nevertheless prudent to test the limits of our ability to make a physical characterization. For this characterization, we proceed with our favored interpretation and subsequent assumption that Apophis is most closely analogous to LL chondrite meteorites whose small scale physical properties are available from laboratory measurements. As noted below, we can also benefit greatly from *in situ* measurements of a possibly comparable Asteroid (25143) Itokawa, for which both groundbased and spacecraft results predominantly support a similar LL chondrite compositional interpretation (Binzel et al., 2001; Abe et al., 2006; Okada et al., 2006).

Table 2 illustrates the known parameters for LL chondrite meteorites (and hence possibly Apophis) at the microscopic level, derived primarily from the work of Britt and Consolmagno (2003). While we can infer a grain density of 3.5 ± 0.1 g/cm^3 for the basic material of which an asteroid like Apophis may be constructed, an estimate for the total mass (even knowing perfectly the volume) has considerable uncertainty. Fig. 3 demonstrates that even on the small scale, bodies such as Apophis are likely aggregates whose history has been dominated by collisions and whose internal structure is not fully compact. The Kilabo meteorite (Fig. 3), for

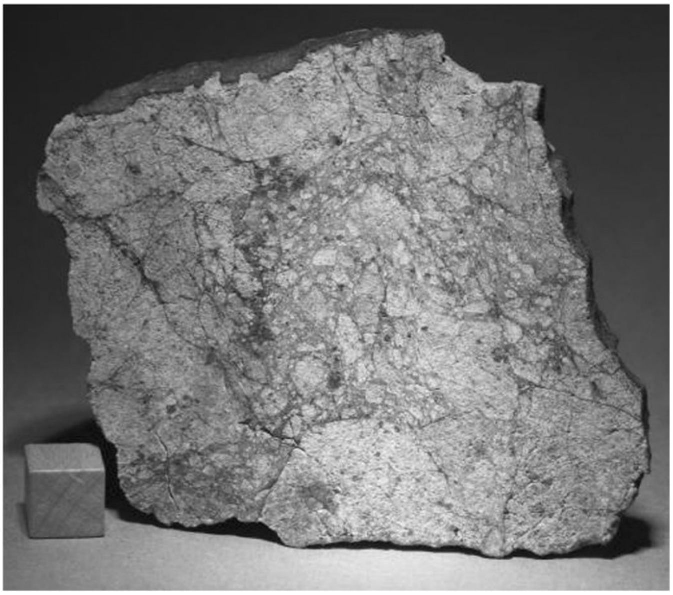

Fig. 3. Interior structure of the Kilabo (LL6) ordinary chondrite meteorite, with a 1 cm cube for scale. Light colored fragments are relithified and welded together within a darker groundmass, evidencing a history of collisional disruption and reaccumulation. Fell at Kilabo, Nigeria (near Hadejia) on July 21, 2002. (Photo credit: Eric Twelker.)

example, shows at the cm scale direct physical evidence of a fractured and brecciated structure. As quantified in Table 2, LL chondrites are porous on the microscopic scale (also called "microporosity") and on average contain approximately 8% void spaces. The macroscopic-scale porosity (or "macroporosity") for an asteroid the size of Apophis we conjecture is almost certainly higher, as its gravity is sufficient to keep a loose conglomeration of fragments together as a "rubble pile," but not sufficient to cause any compaction of internal (microscopic or macroscopic) void spaces (Britt and Consolmagno, 2001). Our estimate of the mass of Apophis, starting with our assumed meteorite analog, is given in the lower portion of Table 2. Assuming only the porosity at the microscopic scale (thus zero macroscopic porosity), and a maximum diameter (330 m) from the range estimated by Delbo et al. (2007), yields a maximum estimate for the mass of 6.1×10^{10} kg. For the case of an impact at a calculated velocity of 12.6 km/s (Chesley, 2005), the corresponding kinetic energy of a hypothetical impact is 1100 equivalent megatons (Mt) TNT. This represents the maximum possible hazard from a hypothetical Apophis impact, which would place it in the middle range of Torino Scale 9 (Binzel, 2000; Morrison et al., 2004), an event which would have regional consequences.

Internal porosity for small bodies provides a direct benefit from the hazard point of view. For any given size impactor, mass and impact energy are inversely proportional to greater values for the porosity. Taking the lower limit (210 m) for Apophis' size estimate (Delbo et al., 2007) and a total (micro plus macro) porosity of 62%, the corresponding minimum estimate for the mass is 0.7×10^{10} kg and the kinetic energy of a hypothetical impact is 105 equivalent megatons (Mt) TNT, a factor of ten below the maximum. At this level, a hypothetical impact by Apophis would be on the border between Torino Scale 8 and 9, suggesting the outcome would represent a local to regional hazard.

To achieve what we offer as the current best estimate for Apophis, we take advantage of the results of *in situ* spacecraft measurements of NEOs. As noted above, the spectral characteristics and our LL chondrite interpretation for Apophis is the same compositional conclusion reached for (25143) Itokawa by the Hayabusa mission (Abe et al., 2006; Okada et al., 2006); with some allowance for the possibility of partial melting. What's more, Itokawa (320 m mean diameter; Fujiwara et al., 2006) and Apophis (210–330 m) are in a comparable size range. Applying directly the knowledge gained by *in situ* exploration, our preferred conjecture for the total porosity of Apophis is picked by assuming the same 40% value found for Itokawa (Abe et al., 2006). Using this total porosity value in conjunction with the average parameters for Apophis (Table 2) yields a mass of 2.0×10^{10} kg and the kinetic energy of a hypothetical impact as 375 equivalent megatons (Mt) TNT, fully consistent with the 400 Mt estimate of Delbo et al. (2007). However as illustrated in Table 2, if this conjecture for the total porosity is not correct, there remains a factor of 2–3 in the range of possible variations in the mass and kinetic energy solutions.

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References

Abe, M., and 12 colleagues, 2006. Near-infrared spectral results of Asteroid Itokawa from the Hayabusa Spacecraft. Science 312, 1334–1338.

Abell, P.A., Vilas, F., Jarvis, K.S., Gaffey, M.J., Kelley, M.S., 2007. Mineralogical composition of (25143) Itokawa 1998 SF36 from visible and near-infrared reflectance spectroscopy: Evidence for partial melting. Meteorit. Planet. Sci. 42, 2165–2177.

Binzel, R.P., 2000. The Torino impact hazard scale. Planet. Space Sci. 48, 297–303.

Binzel, R.P., Bus, S.J., Sunshine, J., Burbine, T., 2001. MUSES-C target Asteroid (25143) 1998 SF36: A reddened ordinary chondrite. Meteorit. Planet. Sci. 36, 1167–1172.

Binzel, R.P., Rivkin, A.S., Stuart, J.S., Harris, A.W., Bus, S.J., Burbine, T.H., 2004. Observed spectral properties of near-Earth objects: Results for population distribution, source regions, and space weathering processes. Icarus 170, 259–294.

Binzel, R.P., Rivkin, A.S., Thomas, C.A., Demeo, F.E., Tokunaga, A., Bus, S.J., 2005. The MIT-Hawaii-IRTF joint campaign for NEO spectral reconnaissance. Lunar Planet. Sci. XXXVI. Abstract 36.1817.

Britt, D.T., Consolmagno, G.J., 2001. Modeling the structure of high porosity asteroids. Icarus 152, 134–139.

Britt, D.T., Consolmagno, G.J., 2003. Stony meteorite porosities and densities: A review of the data through 2001. Meteorit. Planet. Sci. 38, 1161–1180.

Britt, D.T., Yeomans, D., Housen, K., Consolmagno, G., 2002. Asteroid density, porosity, and structure. In: Bottke, W.F., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, pp. 485–500.

Brunetto, R., Vernazza, P., Marchi, S., Birlan, M., Fulchignoni, M., Orofino, V., Strazzulla, G., 2006. Modeling asteroid surfaces from observations and irradiation experiments: The case of 832 Karin. Icarus 184, 327–337.

Bus, S.J., 1999. Compositional structure in the asteroid belt: Results of a spectroscopic survey. Doctoral thesis. Massachusetts Institute of Technology, Cambridge, Massachusetts.

Chesley, S.R., 2005. Potential impact detection for near-Earth asteroids: The case of 99942 Apophis (2004 MN 4). In: IAU Symposium No. 229, pp. 215–228.

Clark, B.E., Hapke, B., Pieters, C., Britt, D., 2002. Asteroid space weathering and regolith evolution. In: Bottke, W.F., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, pp. 585–599.

Delbo, M., Harris, A.W., Binzel, R.P., Pravec, P., Davies, J.K., 2003. Keck observations of near-Earth asteroids in the thermal infrared. Icarus 166, 116–130.

Delbo, M., Cellino, A., Tedesco, E.F., 2007. Albedo and size determination of potentially hazardous asteroids: (99942) Apophis. Icarus 188, 266–269.

DeMeo, F.E., 2007. DeMeo taxonomy: Categorization of asteroids in the near-infrared. Master's thesis. Massachusetts Institute of Technology, Cambridge, Massachusetts.

DeMeo, F.E., Binzel, R.P., Slivan, S.M., Bus, S.J., 2009. An extension of the Bus asteroid taxonomy into the near-infrared. Icarus, submitted for publication.

Dressler, A., Hare, T., Bigelow, B.C., Osip, D.J., 2006. IMACS: The wide-field imaging spectrograph on Magellan–Baade. In: McLean, I.S., Iye, M. (Eds.), Ground-Based and Airborne Instrumentation for Astronomy. In: Proc. of the SPIE, vol. 6269, pp. 62690–62712.

Folco, L., Bland, P.A., D'Orazio, M., Franchi, I.A., Rocchi, S., 2002. Dar Al Gani 896: A unique picritic achondrite. Meteorit. Planet. Sci. Suppl. 37, A49.

Fujiwara, A., and 21 colleagues, 2006. The rubble-pile Asteroid Itokawa as observed by Hayabusa. Science 312, 1330–1334.

Gaffey, M.J., Bell, J.F., Brown, R.H., Burbine, T.H., Piatek, J.L., Reed, K.L., Chaky, D.A., 1993. Mineralogical variations within the S-type asteroid class. Icarus 106, 573–602.

Hiroi, T., Abe, M., Kitazato, K., Abe, S., Clark, B.E., Sasaki, S., Ishiguro, M., Barnouin-Jha, O.S., 2006. Developing space weathering on the Asteroid 25143 Itokawa. Nature 443, 56–58.

Hutchison, R., 2004. Meteorites: A Petrologic, Chemical and Isotopic Synthesis. Cambridge Univ. Press, Cambridge, UK.

Lucey, P.G., 1998. Model near-infrared optical constants of olivine and pyroxene as a function of iron content. J. Geophys. Res. 103 (E1), 1703–1714.

MacRobert, A., 2005. Asteroid 2004 MN4: A really near miss. Sky Telescope 109, 16–17.

McCoy, T.J., Keil, K., Mayeda, T.K., Clayton, R.N., 1992. Monument draw and the formation of the acapulcoites. Lunar Planet. Sci. XXIII, 871–872.

Morrison, D., Chapman, C.R., Steel, D., Binzel, R.P., 2004. Impacts and the public: Communicating the nature of the impact hazard. In: Belton, M., Morgan, T.H., Samarasinha, N., Yeomans, D.K. (Eds.), Mitigation of Hazardous Comets and Asteroids. Cambridge Univ. Press, Cambridge, UK, pp. 353–390.

Okada, T., Shirai, K., Yamamoto, Y., Arai, T., Ogawa, K., Hosono, K., Kato, M., 2006. X-ray fluorescence spectrometry of Asteroid Itokawa by Hayabusa. Science 312, 1338–1341.

Rayner, J.T., Toomey, D.W., Onaka, P.M., Denault, A.J., Stahlberger, W.E., Vacca, W.D., Cushing, M.C., Wang, S., 2003. SpeX: A medium-resolution 0.8–5.5 micron spectrograph and imager for the NASA infrared telescope facility. Publ. Astron. Soc. Pacific 115, 362–382.

Rivkin, A.S., Binzel, R.P., Sunshine, J., Bus, S.J., Burbine, T.H., Saxena, A., 2004. Infrared Spectroscopic Observations of 69230 Hermes (1937 UB) and (19356) 1997 GH3: Possible unweathered endmembers among ordinary chondrite analogs. Icarus 172, 408–414.

Shkuratov, Y., Starukhina, L., Hoffmann, H., Arnold, G., 1999. A model of spectral albedo of particulate surfaces: Implications for optical properties of the Moon. Icarus 137, 235–246.

Stuart, J.S., Binzel, R.P., 2004. Bias-corrected population, size distribution, and impact hazard for the near-Earth objects. Icarus 170, 295–311.

Sunshine, J.M., Pieters, C.M., 1993. Estimating modal abundances from the spectra of natural and laboratory pyroxene mixtures using the Modified Gaussian Model. J. Geophys. Res. 98, 9075–9087.

Vernazza, P., Binzel, R.P., Thomas, C.A., DeMeo, F.E., Bus, S.J., Rivkin, A.S., Tokunaga, A.T., 2008. Compositional differences between meteorites and near-Earth asteroids. Nature 454, 858–860.

Zipfel, J., Palme, H., 1993. Chemical composition of new acapulcoites and lodranites. Lunar Planet. Sci. XXIV, 1579–1580.