LETTERS

Earth encounters as the origin of fresh surfaces on near-Earth asteroids

Richard P. Binzel[1,2], Alessandro Morbidelli[3], Sihane Merouane[4], Francesca E. DeMeo[4], Mirel Birlan[2], Pierre Vernazza[5], Cristina A. Thomas[6], Andrew S. Rivkin[7], Schelte J. Bus[8] & Alan T. Tokunaga[8]

Telescopic measurements of asteroids' colours rarely match laboratory reflectance spectra of meteorites owing to a 'space weathering'[1,2] process that rapidly[3] reddens asteroid surfaces in less than 10^6 years. 'Unweathered' asteroids (those having spectra matching the most commonly falling ordinary chondrite meteorites), however, are seen among small bodies the orbits of which cross inside Mars and the Earth. Various explanations have been proposed for the origin of these fresh surface colours, ranging from collisions[4] to planetary encounters[5]. Less reddened asteroids seem to cross most deeply into the terrestrial planet region, strengthening[6] the evidence for the planetary-encounter theory[5], but encounter details within 10^6 years remain to be shown. Here we report that asteroids displaying unweathered spectra (so-called 'Q-types'[7]) have experienced orbital intersections closer than the Earth–Moon distance within the past 5×10^5 years. These Q-type asteroids are not currently found among asteroids showing no evidence of recent close planetary encounters. Our results substantiate previous work[5]: tidal stress[8], strong enough to disturb and expose unweathered surface grains, is the most likely dominant short-term asteroid resurfacing process. Although the seismology details are yet to be worked out, the identification of rapid physical processes that can produce both fresh and weathered asteroid surfaces resolves the decades-long[9] puzzle of the difference in colour of asteroids and meteorites.

We performed our analysis on a sample of 95 Earth- and Mars-crossing asteroids for which we have visible and near-infrared spectral measurements (Supplementary Table 1) displaying absorption band characteristics corresponding to the S-, Sq-, and Q-type classes within asteroid taxonomy[10] (Fig. 1). The Q-types we sampled span the H magnitude range of 14.0 to 20.8, corresponding to approximate diameters of between 4 km and 200 m. (To avoid possible bias effects arising from comparing asteroids over different size ranges, our total sample of 95 objects is constrained within this H magnitude range.) We use the Minimum Orbit Intersection Distance (MOID)[11] for evaluating the possibility of Earth encounters that are recent compared with the $<10^6$-year space weathering timescale[3]. Although the MOID parameter tells us how nearly two objects can encounter each other, it does not tell whether the two objects actually have an encounter at this minimum distance. Computationally, this distinction arises because the precision of knowing the object's position in the orbit deteriorates (the uncertainty increases) much more rapidly than the knowledge of the orbit itself. Therefore, for most orbital investigations longer than a few centuries, MOID can be used only to evaluate the possibility of encounters and not as a method of prediction for specific encounter events.

Figure 2a shows the distribution of current MOID values, where the higher concentration of 'fresh and unweathered' Q-type asteroids towards the closest Earth encounters motivated our more detailed analysis. MOID is not a static value; it changes as the asteroid's orbit is perturbed, primarily by Jupiter and the terrestrial planets (including planetary encounters). We explored the past MOID evolution of our sample by performing a 500,000-year symplectic algorithm[12] integration using the swift_rmvs3 code[13] (with a 3.65-day timestep for accuracy in determining close encounters, and output values computed at 50-year intervals), accounting for the eight planets Mercury to Neptune. Our integrations for each asteroid included six additional 'clones' (test particles with the same initial position, offset with velocities differing by $\pm 10^{-6}$ astronomical units (AU) per

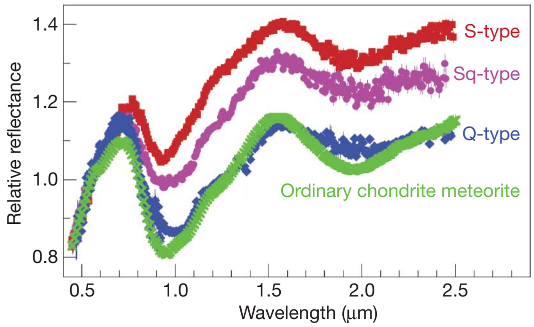

Figure 1 | Reflectance spectra properties of ordinary chondrite meteorites compared with asteroids grouped according to taxonomic types. Taxonomic classification constitutes our first step in asteroid spectral analysis and we apply the Bus–DeMeo method[10], which groups measurements according to characteristics in the broad 1-μm and 2-μm absorption bands arising from the presence of the minerals olivine and pyroxene in both meteorites and asteroids[26]. Asteroids categorized as Q-types[7] are those showing the spectral properties and mineralogic interpretations most analogous to laboratory measurements of the most commonly falling class of meteorites, the ordinary chondrites. Progressively more red-sloped asteroid spectra with diminished absorption bands near the 1-μm and 2-μm wavelengths are classified as Sq- and S-types (see the Supplementary Information). We interpret Q-type asteroids to have fresh ordinary-chondrite-like compositions that have not been altered by space weathering[1,2] processes, whereas Sq- and S-types may be ordinary chondrite asteroids the surfaces of which have experienced increasing amounts of weathering as a result of being exposed to the space environment for longer[3] times. The objects shown are the LL4 ordinary chondrite Greenwell Springs[27]; asteroids 1862 Apollo (Q), 1685 Toro (Sq), and 719 Albert (S). Error bars on all measurements denote one-sigma uncertainties.

[1]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA. [2]Institut de Mecanique Celeste et de Calcul des Ephemerides (IMCCE), Observatoire de Paris, Paris 75014, France. [3]Departement Cassiopee, Université de Nice Sophia-Antipolis, CNRS, Observatoire de la Côte d'Azur, Nice 06304, France. [4]Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique (LESIA), Observatoire de Paris, Meudon 92195, France. [5]ESTEC/ESA, Noordwijk 2200 AG, Netherlands. [6]Department of Physics and Astronomy, Northern Arizona University, Flagstaff, Arizona 86011, USA. [7]Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland 20723, USA. [8]Institute for Astronomy, University of Hawaii, Hilo, Hawaii 96720, USA.

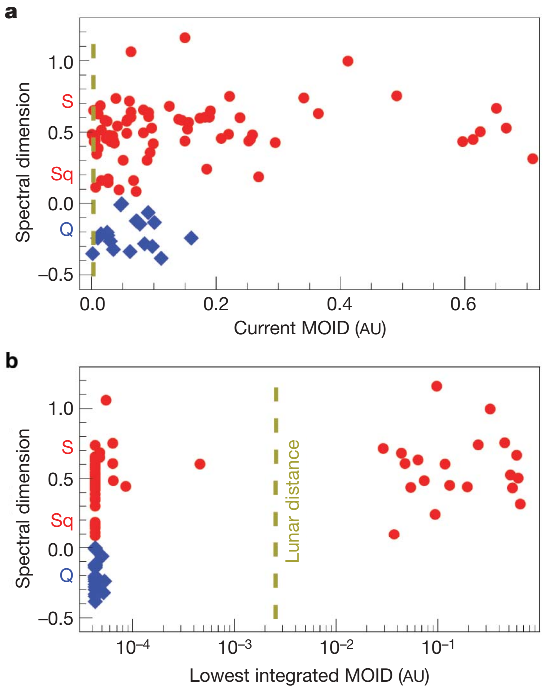

Figure 2 | Distributions for the orbit intersection distances for weathered and fresh asteroids. As its name implies, the minimum orbit intersection distance (MOID) measures the minimum distance separating the two closest points between the Earth's orbit and the orbit of a test particle (asteroid). **a**, For the values of the MOID at the current epoch, fresh Q-type asteroids typically have closer Earth intersection distances than the overall sample. **b**, Q-types appear much more strongly concentrated towards very close Earth intersection distances when their long-term orbital behaviour over the past 500,000 years is taken into account. Here we plot the lowest MOID value found among the 70,000 integrations performed for each object. Effectively, all objects that have a MOID value inside the orbit of the Moon within the past 500,000 years also present minimum intersection distances less than or equal to the Earth radius. (The vertical alignment of points on the left corresponds to one Earth radius; the fact that these objects exist today illustrates that the MOID history does not itself indicate the distance of an actual encounter.) All fresh Q-types in our sample show orbital histories capable of Earth approaches less than the lunar distance (vertical dashed line). Importantly, for all objects that have orbital histories keeping them removed from Earth encounters (demonstrated by having MOID values well outside the lunar distance), none have fresh Q-type surfaces. The vertical scale is related to the asteroid's spectral classification as a Q-, Sq-, or S-type; it measures the distance from the boundary[10] defining the Q-types. The plotted vertical value is a dimensionless scaler in principal component space, defined by the spectral variance of the asteroid population as a whole after the removal of spectral slope. (See the Supplementary Information.) Increasing values reflect diminishing spectral absorption bands, a trend consistent with increasing amounts of space weathering[28].

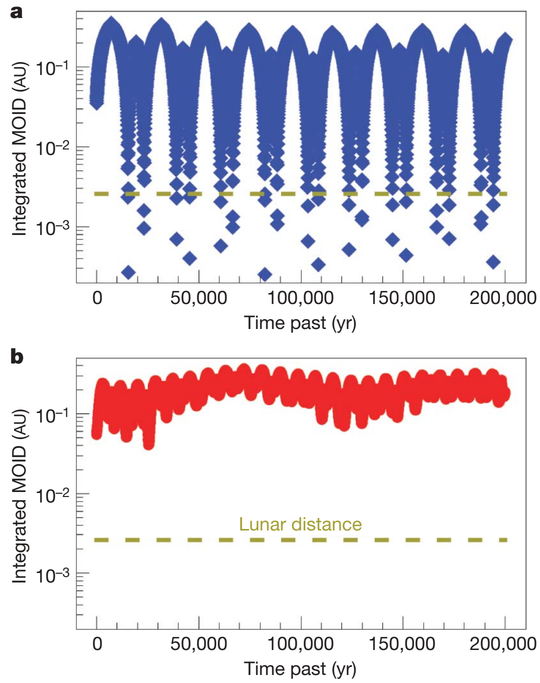

Figure 3 | Comparison of typical long-term orbital evolution behaviour for objects inside the orbits of Earth and Mars. Although both asteroids currently cross the orbits of Earth and Mars, asteroid 1566 Icarus (**a**) shows that its minimum orbit intersection distance (MOID) allows multiple close approaches to Earth well inside the lunar distance, while asteroid 136993 (**b**) does not. Close approaches for 136993 do not occur because its (present to 500,000 years ago) orbit consistently intersects the Earth's well above the Earth's orbital plane. The horizontal line represents the lunar distance of 0.00257 AU. The timescale of the figure is back 200,000 years, allowing the structure of the orbital evolution to be seen.

year in each Cartesian component) to explore the range of possible orbital evolution. The results of exploring more than half a million evolved MOID values (Fig. 2b) reveals two groupings within our observational sample: objects capable of making particularly close approaches to the Earth and those for which no close approach is revealed (Fig. 3). We use the Earth–Moon distance as a convenient proxy for defining 'close approach': any object for which the MOID can become nearly zero will more frequently present *cis*-lunar MOID values that can be found in a discrete integration (such as ours). Conversely, for the objects that are protected from Earth encounters, the MOID at all times remains substantially beyond the lunar distance. We find that 75 out of 95 objects in our sample have the possibility of experiencing a close Earth approach within the past 500,000 years, including all 20 out of 20 of the Q-type asteroids. Our MOID calculations reveal no evidence of close Earth approaches for the 20 other objects in our sample (and none of their 120 clones), indicating that they almost certainly did not encounter the Earth within the past 500,000 years.

What is the significance of finding that all 20 Q-type asteroids have minimum intersection distances closer than the lunar orbit? Applying binomial statistics, we first note that for any object randomly selected from the sample there is a $75/95 = 78.9\%$ likelihood of it satisfying the 'close approach' criterion of having the MOID value smaller than the Moon's orbit. For 20 objects randomly selected from the sample, the binomial probability ($P = 0.789$ for individual success) of all 20 objects satisfying the close approach criterion is only 0.009. Consequently we can say with 99.1% statistical confidence that the MOID distribution of Q-type asteroids is not random. Thus we conclude that Q-types are a class of asteroids that show a strong correlation with orbital history allowing for an Earth encounter at least as close as the lunar distance within the past few hundred thousand years.

If this conclusion is correct, that a Q-type asteroid spectrum is indicative of a recent close-to-Earth approach, then a critical corollary must be examined: Q-types should be rare or absent among those objects devoid of recent planetary encounters. So far this has been the case in main-belt asteroid spectroscopic surveys[14–16], although most such surveys are magnitude-limited such that they cannot include objects in the kilometre and sub-kilometre size range, which is the comparable size range of near-Earth objects. We can consider our own sample to be a survey of asteroids in the inner Solar System, dividing them into separate sample populations of 'encountering' and 'non-encountering' objects. To reduce the possibility of a size-dependent bias, we allow the 14.0 to 18.5 H magnitude range set by our 20-member non-encountering population to restrict the membership of our encountering object comparison set to the 54 objects (including 12 Q-types) that fall in the same magnitude range. If Q-types are randomly distributed within the inner Solar System regardless of encounter history, then we would expect a $12/54 = 22.2\%$ likelihood of finding a Q-type spectrum for each member of the non-encountering population. For 20 objects in the non-encountering population (having binomial probability of individual success $P = 0.222$), the random chance that 0 out of 20 would be Q-types is only 0.007. Thus we arrive at a similar statistical confidence level (99.3%) that Q-type asteroids are correlated with recent Earth encounters. What about Venus and Mars encounters? We speculate that there could be Q-type objects with small MOID values relative to Venus but not relative to the Earth, but they are not present in our data set. (Our Earth-based observations are highly biased to near-Earth objects rather than near-Venus objects.) Critically, none of the 20 objects that avoid encounters with the Earth have small MOID values relative to Venus. All of these 20 objects do have a small MOID relative to the orbit of Mars, but the interactive efficiency of Mars is a hundred times less effective than the Earth's (because its mass is a tenth that of the Earth). Thus Earth encounters are the dominant planetary factor for the effect present in our data.

Our presumption[5] is that a close Earth encounter creates a tidal stress[8] causing the body to deform slightly or perhaps undergo a more periodic type of seismic vibration. The resulting redistribution of surface material can effect an observable spectral change, as revealed by *in situ* spacecraft measurements of fresh downslope regolith on S-type asteroids (that is, asteroids with overall space-weathered ordinary chondrite surfaces). Examples include fresh colours on the northern wall of the crater Psyche and the eastern and western walls of the saddle Himeros[17] for asteroid Eros and fresher colours in areas of steeper slopes such as the Little Woomera region[18] for asteroid Itokawa.

Of the 75 objects the lowest MOID values of which are well inside the lunar distance, we surmise from the observations that 27% (20/75 being Q-types) experienced an actual Earth encounter inside a critical limit within the past few hundred thousand years. To find this critical distance, we examined our computational statistics (in addition to the MOID calculation we tracked the actual encounter distance in the simulation for $75 \times 7 = 525$ test particles, including clones), finding that $145/525 = 28\%$ passed within 16 Earth radii. Can encounters at this distance have any effect? Whereas encounters near the Roche limit are demonstrated[8,19] to deform substantially (and consequently totally resurface) an asteroid, the magnitude of the effect required to correspond to our observations merely has to be sufficient to disturb the angle of repose for asteroid regolith grains, perhaps by triggering small landslides that expose fresh and unweathered material[17,18]. At present it is not well understood how close is 'close enough' to precipitate such surface rejuvenation, but the conditions undoubtedly depend on complex seismic factors such as the velocity and duration of the encounter, the object's shape, internal structure, surface gravity, local slopes, rotation rate and orientation, and the nature of the pre-existing regolith and its cohesion.

We assume there to be an equilibrium between the frequency of freshening encounters and the space weathering rate, which gives us a useful constraint on these seismic factors. We express this constraint as: $(s/R_E)^2(T_c/T_w) = 0.27$, where s is the encounter distance, R_E is the Earth radius, T_w and T_c are the weathering and Earth impact rates (gravitational focusing is ignored; the constant 0.27 comes from our observational sample, above). For the near-Earth population[20] at 1 km, T_c for individual objects is $\sim 10^{-9}$ per year. Accordingly, for a space weathering rate of 10^{-6} per year (ref. 3), our equilibrium constraint suggests seismically effective surface changes occur for encounters inside $\sim$16 Earth radii. We emphasize the considerable uncertainties in this 16-Earth-radii estimate, but the consistency of reaching this estimate from independent considerations is striking and gives us confidence that this is an important starting point for follow-up studies on the detailed mechanics for resurfacing processes. (Our first 16-Earth-radii result above comes from numerical simulations; this second 16-Earth-radii result is independently constrained by the space weathering rate of 10^{-6} per year (ref. 3). A faster space weathering rate pushes this distance outward to allow for more encounters in a shorter time.)

In the context of asteroid–meteorite connections, an equilibrium between fast space-weathering timescales[3] and frequent surface-refreshing Earth encounters helps to resolve the decades-long[9] 'ordinary chondrite problem': why do relatively few asteroids reveal telescopic spectra closely matching the most common meteorites? (Ordinary chondrites constitute 80% of all current falls[21].) Although *in situ* elemental abundance measurements[22] of the 'weathered' S-type asteroid 433 Eros reveal that ordinary chondrite compositions may be sufficiently abundant to account for their dominance of the meteorite flux, the relative rarity of telescopic spectral matches remains unexplained. In particular, why are the observed spectral matches so exclusive to the near-Earth asteroid population? (As we noted above, ordinary chondrite spectral matches are effectively absent among main-belt asteroids[14–16].)

From our new observations and orbital evolution analysis, we conclude that these remaining issues of the 'ordinary chondrite problem' can be understood as resulting from the competition between two rapid processes: planetary encounters, as was previously proposed[5] and preliminarily substantiated[6], freshen asteroid surfaces at a rate just slightly faster than space weathering[3] can alter them. So the clue to the main reason that only near-Earth asteroids (thus far) reveal unweathered surfaces matching ordinary chondrite meteorites has been in their name all along. The general absence of fresh spectral signatures for non-encountering asteroids (including main-belt asteroids observed so far) suggests that other processes like collisions[4] or spin-up to the point of fission by radiation forces[23], although potentially capable of refreshing the surfaces of asteroids, are much less efficient than tidal effects. These effects may be directly testable during the 2029 encounter (at about six Earth radii) of asteroid 99942 Apophis, whose current spectral colours[24] put it in the weathered (Sq) category. A prior prediction[25] for a dramatic alteration in Apophis' spin state during encounter supports the likelihood of substantial regolith redistribution even for an encounter well outside the Roche limit.

Received 2 October; accepted 18 November 2009.

1. Clark, B. E., Hapke, B., Pieters, C. & Britt, D. in *Asteroids III* (eds Bottke, W. F., Cellino, A., Paolicchi, P. & Binzel, R. P.) 585–589 (University of Arizona Press, 2002).
2. Chapman, C. R. Space weathering of asteroid surfaces. *Annu. Rev. Earth Planet. Sci.* **32**, 539–567 (2004).
3. Vernazza, P., Binzel, R. P., Rossi, A., Fulchignoni, M. & Birlan, M. Solar wind as the origin of rapid weathering of asteroid surfaces. *Nature* **458**, 993–995 (2009).
4. Binzel, R. P. *et al.* Observed spectral properties of near-Earth objects: results for population distribution, source regions, and space weathering processes. *Icarus* **170**, 259–294 (2004).
5. Nesvorný, D., Jedicke, R., Whiteley, R. J. & Ivezic, Z. Evidence for asteroid space weathering from the Sloan Digital Sky Survey. *Icarus* **173**, 132–152 (2005).
6. Marchi, S., Magrin, S., Nesvorný, D., Paolicchi, P. & Lazzarin, M. A spectral slope versus perihelion distance correlation for planet-crossing asteroids. *Mon. Not. R. Astron. Soc.* **368**, 39–42 (2006).
7. McFadden, L. A., Gaffey, M. J. & McCord, T. B. Near-earth asteroids—possible sources from reflectance spectroscopy. *Science* **229**, 160–163 (1985).
8. Richardson, D. C., Bottke, W. F. & Love, S. G. Tidal distortion and disruption of Earth-crossing asteroids. *Icarus* **134**, 47–76 (1998).
9. Wetherill, G. W. & Chapman, C. R. in *Meteorites and the Early Solar System* (eds Kerridge, J. F. & Matthews, M. S.) 35–67 (University of Arizona Press, 1988).
10. DeMeo, F. E., Binzel, R. P., Slivan, S. M. & Bus, S. J. An extension of the Bus asteroid taxonomy into the near-infrared. *Icarus* **202**, 160–180 (2009).
11. Bonanno, C. An analytical approximation for the MOID and its consequences. *Astron. Astrophys.* **360**, 411–416 (2000).
12. Wisdom, J. & Holman, M. Symplectic maps for the n-body problem. *Astron. J.* **102**, 1528–1538 (1991).
13. Levison, H. F. & Duncan, M. J. The long-term dynamical behavior of short-period comets. *Icarus* **108**, 18–36 (1994).
14. Zellner, B., Tholen, D. J. & Tedesco, E. F. The eight-color asteroid survey: results for 589 minor planets. *Icarus* **61**, 355–416 (1985).
15. Bus, S. J. & Binzel, R. P. Phase II of the small main-belt asteroid spectroscopic survey. *Icarus* **158**, 106–145 (2002).
16. Lazzaro, D. *et al.* S3OS2: the visible spectroscopic survey of 820 asteroids. *Icarus* **172**, 179–220 (2004).

17. Murchie, S. R. *et al.* Color variations on Eros from NEAR multispectral imaging. *Icarus* **155,** 145–168 (2002).
18. Saito, J. *et al.* Detailed images of asteroid 25143 Itokawa from Hayabusa. *Science* **312,** 1341–1344 (2006).
19. Holsapple, K. A. & Michel, P. Tidal disruptions: a continuum theory for solid bodies. *Icarus* **183,** 331–348 (2006).
20. Stuart, J. S. & Binzel, R. P. Bias-corrected population, size distribution, and impact hazard for the near-Earth objects. *Icarus* **170,** 295–311 (2004).
21. Grady, M. M. *Catalogue of Meteorites* 689 (Cambridge University, 2000).
22. Trombka, J. I. *et al.* The elemental composition of asteroid 433 Eros: results of the NEAR-Shoemaker X-ray spectrometer. *Science* **289,** 2101–2105 (2000).
23. Scheeres, D. J. The dynamical evolution of uniformly rotating asteroids subject to YORP. *Icarus* **188,** 430–450 (2007).
24. Binzel, R. P. *et al.* Spectral properties and composition of potentially hazardous asteroid (99942) Apophis. *Icarus* **200,** 480–485 (2009).
25. Scheeres, D. J. *et al.* Abrupt alteration of asteroid 2004 MN4's spin state during its 2029 Earth flyby. *Icarus* **178,** 281–283 (2005).
26. Gaffey, M. J., Cloutis, E. A., Kelly, M. S. & Reed, K. L. in *Asteroids III* (eds Bottke, W. F., Cellino, A., Paolicchi, P. & Binzel, R. P.) 183–204 (University of Arizona Press, 2002).
27. Burbine, T. H., McCoy, T. J., Jarosewich, E. & Sunshine, J. M. Deriving asteroid mineralogies from reflectance spectra: implications for the Muses-C target asteroid. *Antarct. Meteor. Res.* **16,** 185–195 (2003).
28. Strazzulla, G. *et al.* Spectral alteration of the meteorite Epinal (H5) induced by heavy ion irradiation: a simulation of space weathering effects on near-Earth asteroids. *Icarus* **174,** 31–35 (2005).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements R.P.B. is a Chercheur Associé at the Observatoire de Paris IMCCE and thanks IMCCE and LESIA for their collaboration and hospitality during the initiation of this analysis. We thank C. Chapman, B. Clark, D. Richardson and D. Nesvorný for their constructive reviews and comments. Observations reported here were obtained at the Infrared Telescope Facility, which is operated by the University of Hawaii under Cooperative Agreement NCC 5-538 with the National Aeronautics and Space Administration, Science Mission Directorate, Planetary Astronomy Program. This paper includes data gathered with the 6.5 m Magellan Telescopes located at Las Campanas Observatory, Chile. F.E.D. acknowledges funding from the Fulbright Program. This material is based upon work supported by the National Science Foundation under grant 0506716 and NASA under grant NAG5-12355. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation or NASA.

Author Contributions R.P.B. and A.T.T. served as principal investigators for a joint observing programme to acquire the near-infrared spectral data. Most data were acquired by R.P.B., C.A.T. and F.E.D., while F.E.D. performed most of the processing and taxonomic evaluation. Processing routines were developed by S.J.B., A.S.R. and R.P.B. The scientific analysis was directed by R.P.B. with the first stages performed by S.M. with input from M.B. and P.V. A.M. performed all of the orbital integrations. R.P.B. and A.M. worked jointly to draft the manuscript with all authors reviewing and contributing to its final form.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Correspondence and requests for materials should be addressed to R.P.B. (rpb@mit.edu).