Water ice and organics on the surface of the asteroid 24 Themis

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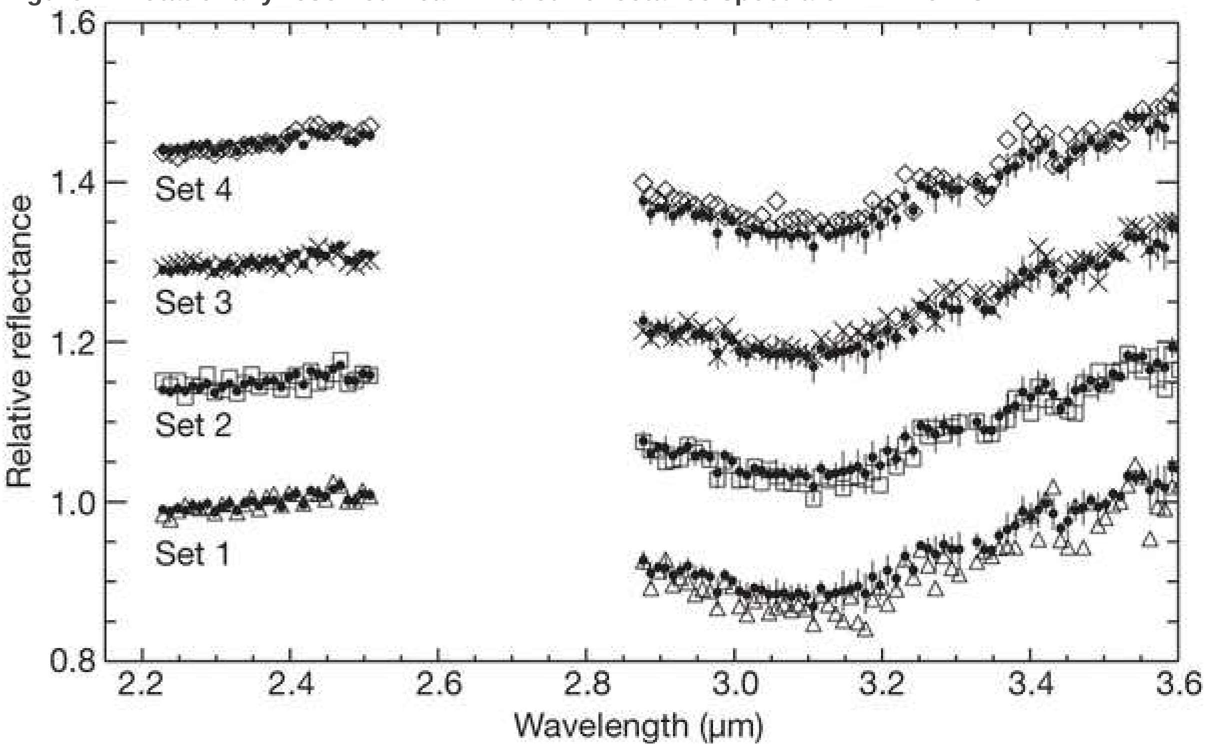
ABSTRACT

It has been suggested[1, 2, 3] that Earth's current supply of water was delivered by asteroids, some time after the collision that produced the Moon (which would have vaporized any of the pre-existing water). So far, no measurements of water ice on asteroids[4, 5] have been made, but its presence has been inferred from the comet-like activity of several small asteroids, including two members of the Themis dynamical family[6]. Here we report infrared spectra of the asteroid 24 Themis which show that ice and organic compounds are not only present on its surface but also prevalent. Infrared spectral differences between it and other asteroids make 24 Themis unique so far, and our identification of ice and organics agrees with independent results[7] that rule out other compounds as possible sources of the observed spectral structure. The widespread presence of surface ice on 24 Themis is somewhat unexpected because of the relatively short lifetime of exposed ice at this distance (~3.2 AU) from the Sun. Nevertheless, there are several plausible sources, such as a subsurface reservoir that brings water to the surface through 'impact gardening' and/or sublimation.

The asteroid 24 Themis is the largest member of the Themis dynamical family. This family resulted from a large collision more than 1.0 Gyr ago[8] and lies ~3.2 AU from the Sun in low-inclination orbits. Two small members of this family are also known as 'main-belt comets' (MBCs) because they show dust tails[6]. However, the orbits of these MBCs are very unlikely to have evolved from either of the known comet reservoirs: the trans-Neptunian region or the Oort cloud. Furthermore, their visible spectra resemble those of the larger family members and not those of cometary nuclei[9]. Nevertheless, it has been proposed that the activity in these MBCs is driven by the same process that occurs in typical comets, that is, sublimation of surface ice[6]. This ice in MBCs might be primordial and would have been protected from insolation since the time of formation by a poorly conducting surface layer[10]. Sublimation could start with a collision able to penetrate this inactive layer, exposing the ice to sunlight[6].

The unusual behaviour of these two small family members made the characterization of the surface composition of 24 Themis an important observational priority. Because the near-infrared region can be very diagnostic of the composition of asteroids[11], we obtained spectroscopy at wavelengths from 2 to 3.6 μm, using NASA's 3.0-m Infrared Telescope Facility on 23 January 2008 UT, over a period of 7 h (84% of this asteroid's 8.37-h rotational period). Our infrared reflectance spectra of 24 Themis at four rotational phases are shown in Fig. 1 (details of the data analysis are provided in the Supplementary Information). Our observations show a well-defined 3.1-μm absorption band with a similar shape and depth at all rotational phases. The shape of this absorption in 24 Themis is unique so far. Although many asteroids show absorptions in this region, they are well matched by hydrated minerals[5, 11]. The 24 Themis 3.1-μm feature is significantly different from those in other asteroids, in all meteorites and in all plausible mineral samples available[5, 7, 12, 13, 14]. We have modelled the shape of the 3.1-μm absorption in this asteroid and we show that it is accurately matched by small ice particles (Supplementary Information). We emphasize that our identification of water ice agrees with independent results that also rule out other compounds as sources of this absorption[7].

Figure 1: Rotationally resolved near-infrared reflectance spectra of 24 Themis.



The shape and wavelength of the 3.1-μm absorption in this asteroid is interpreted here and in the companion Letter[7] as being due to water ice as opposed to hydrated minerals. There are also absorptions in all our spectra between 3.3 and 3.6 μm that are closely matched by organic compounds[22]. To facilitate searching for possible rotational variation, we grouped the spectra into four separate time intervals, which are plotted in this figure (open symbols and crosses) along with the mean of all our reflectance spectra (solid dots). To plot the reflectance spectrum, we remove the solar spectrum and any thermal emission; at the longest wavelength, 3.6 μm, the subtracted thermal contribution was approximately 20%. The spectra have been normalized at 2.4 μm and for clarity each set is offset from the previous one by 0.15 in relative reflectance. The uncertainties are only plotted for the mean spectrum; error bars correspond to 1 s.d. and the spectral resolution ($\lambda/\Delta\lambda$; λ, wavelength) is ~100. We omit the spectral region from 2.45 to 2.83 μm because the Earth's atmosphere is essentially opaque at these wavelengths. We note that the ice and organics absorption bands, at 3.1 μm and between 3.3 and 3.6 μm, preserve their shape and depth throughout the rotation of the asteroid; that is, there is not a significant deviation from the mean in any of the four spectral sets. Hence, the ice and organics are widespread on the surface of this asteroid..

The presence and constant depth of the 3.1-μm absorption in all our spectra suggests that the ice is evenly distributed over the surface. In fact, our rotationally resolved spectra, combined with the orbital coverage reported in the companion Letter[7], sample the spectra of the entire surface. The global coverage of this asteroid achieved by our spectroscopy is independent of the orientation of its spin axis, which remains uncertain[15]. At first glance, the presence and widespread distribution of surface ice on 24 Themis is unexpected because a layer of dirty ice (that is, ice with the same albedo as the asteroid) would sublimate at a rate of roughly 1 m yr^{-1} at this heliocentric distance[6, 16]. Furthermore, on typical active comets, such as 9P/Tempel, ice is mainly below the surface and covers only a small fraction of the comet nucleus[17].

We consider several possible sources of this surface ice on 24 Themis. Stable ice may exist in a subsurface reservoir that is tapped by impact gardening, sublimation or both. Recent work[10] explores the loss rate of buried ice within the top few metres in main-belt asteroids. According to that work, the long-term stability of ice in the shallow subsurface layer (~1–10 m deep) of Themis family member and MBC 7968 Elst-Pizarro is plausible and may be the source of the current exposed ice that drives its cometary activity. Using the orbital and rotational parameters for 24 Themis, the same model[10] predicts that 24 Themis can also retain shallow subsurface ice over the age of the Solar System. In addition, a subsurface ice reservoir could also be present if 24 Themis underwent differentiation resulting in a rocky core and an ice mantle. This type of differentiation has been experienced by the icy satellites of the giant planets, and possibly by the dwarf planet 1 Ceres[18] and some trans-Neptunian objects[19, 20]. However, as long as the ice is no more than a few metres below the surface, the presence of a differentiated ice mantle would be equivalent to that of the 'buried snow line'[10] for the purposes of explaining our detection.

A shallow ice reservoir makes our detection of surface ice easier to explain. A plausible mechanism for exposing buried ice is impact gardening, which on the Moon overturns material at a rate of 1 m Gyr^{-1} (ref. 21). Although an impact gardening rate for 24 Themis has not been determined, it is conceivably large enough to expose, or bring close to the surface, sufficient ice to account for our observations (Supplementary Information). In addition to, or instead of, impact gardening, there may be sublimation activity within this asteroid that deposits a thin frost on the surface. Daily or orbital thermal pulses reaching a subsurface layer of ice could produce this sublimation, and frost would form if the resulting water vapour encountered a cold surface (at night time, in winter or at aphelion). Current sublimation activity may be a non-equilibrium process because any ice that might have originally formed within reach of the daily or orbital thermal pulse should have already sublimated[10]. A possible reason for current activity may be a recent change in the obliquity of the spin pole of 24 Themis.

We also considered, but do not favour, a situation in which a recent comet impact coated 24 Themis with ice. An argument against a recent impact is that the dust signature would probably have been detected in the form of a dust band[8].

Finally, we address the spectral structure beyond 3.3 μm, which is not explained by the presence of ice. Specifically, there are absorptions in all our spectra between 3.3 and 3.6 μm that we can closely match by including organic compounds[22] in our models (Supplementary Fig. 2). Although some mineral compounds have structure in this spectral region, the best fit by far is obtained when we add organics[22] to our water-ice model. The same identification of this spectral structure with organic material is made in the companion Letter[7]. The possible presence of organics on this asteroid makes it even more interesting. For example, the most primitive meteorites have abundant organic molecules; hence, the identification and further study of organic compounds in asteroids may help identify the source region of these rare meteorites.

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