Reports

Hektor: The Largest Highly Elongated Asteroid

Abstract. *New observations of Trojan asteroid 624, Hektor, in April 1979 establish that the high amplitude of the rotational light curve of this object is caused by its elongated shape and not by patches of dark and light albedo on opposing hemispheres. These observations confirm that Hektor is a very unusual object and are consistent with the hypothesis that it may be a compound asteroid formed when two Trojans of comparable size fell together—a rare fossilized example of a planetary accretion process.*

The Trojan asteroids are two groups of minor planets trapped in the Lagrangian points 60° ahead of and behind Jupiter in Jupiter's orbit. Dunlap and Gehrels (*1*) discovered that asteroid 624, Hektor, the brightest Trojan, has one of the largest amplitudes found among asteroid light curves. The brightness can change by as much as a factor of 3.1 during Hektor's 6.9-hour rotation. The amplitude depends on the geometry of observation, since Hektor's rotational pole lies near the ecliptic. Dunlap and Gehrels inferred that the light curve amplitude is probably due to a very elongated shape, but had no proof that the variations were not due to albedo markings. Cruikshank (*2*) and Hartmann and Cruikshank (*3*) established that the two polar faces of Hektor have a very low average albedo so that Hektor is much larger than had first been thought. Its currently estimated dimensions are about 150 by 300 km [122 by 325 km in the Dunlap-Gehrels cylindrical configuration, 153 by 298 km in our compound model (*3*)]. Degewij (*4*) found that other Trojans have light curve amplitudes of only 10 to 20 percent and are evidently roughly spheroidal.

As reviewed in more detail in (*3*), these observations make Hektor a very puzzling object. The conventional explanation for an elongated asteroid is that it is a splinter-shaped fragment of a larger body, but in Hektor's case this would require one huge splinter-shaped fragment with a swarm of smaller spheroidal fragments, all trapped in the same cloud and therefore presumably originating from some unknown, still larger parent Trojan, with no obvious cause for the fragmentation. This scenario seems ad hoc and unappealing. An alternative explanation is that Hektor is a spheroidal object with one dark and one light hemisphere, like Saturn's satellite Iapetus. This would also be extraordinary, however, since Hektor has no obvious preferred orientation in space, while the albedo variations of Iapetus are correlated with the leading and trailing hemispheres and are believed to be associated with a sweepup of debris as Iapetus moves in its orbit, keeping one face tidally locked toward Saturn.

Furthermore, most of the known highly elongated asteroids are among the smallest known asteroids—only a few kilometers in length—and make plausible fragments. By contrast, among the thousands of asteroids Hektor ranks about 21st in dimension and its light curve is the third highest in amplitude.

We (*3*) attempted to explain these properties with a more physical model than had been suggested earlier, namely that Hektor formed during a relatively low-velocity collision of two earlier spheroidal Trojans, which had insufficient energy to completely fragment each other and thus formed a partially fragmented, compound asteroid with an elongated or dumbbell-like shape. The collision might have been the result of inward spiraling during tidal evolution of a co-orbiting pair (very low speed), or it might have been a random low-speed collision of two neighboring objects in the Trojan cloud. The tidal idea requires an explanation for the initial co-orbiting pair, while the collision of two field asteroids appears to require a somewhat lower approach velocity than would be typical for Trojan asteroids (*5*). Nonetheless, this model of Hektor's formation through collision is apparently the only published physical hypothesis for Hektor's origin, and it offers the possibility of an actual example of the coalescence of two primitive planetesimals—the process widely hypothesized to be responsible for the formation of planets. Hektor could thus be not only an interesting but an important object in understanding the history of the solar system.

A nagging problem throughout all this work was lack of proof that Hektor is actually elongated. We have tested this by obtaining nearly simultaneous light curves in reflected sunlight and thermal infrared. In this way we can discriminate a light curve caused by shape from a light curve caused by albedo patchiness as follows. If the light curve is caused pri-

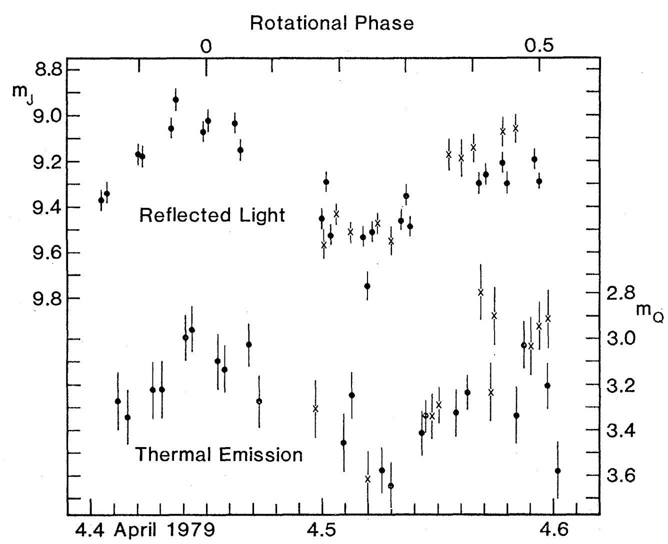

Fig. 1. Comparison of simultaneous light curves of Trojan asteroid 624, Hektor, in reflected sunlight (1.2 μm) and thermal radiation (20 μm), shown in stellar magnitudes m_J and m_Q. Consistent phase and amplitude of the curves shows that Hektor's light variations are due to an unusually elongated shape, not albedo patchiness. Solid points are 4 April 1979 observations, and crosses are 5 April observations adjusted to the 4 April time scale by three cycles of the 6.9225-day rotation period. Error bars for all data points are 1 standard deviation, excluding possible errors in the absolute calibration.

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marily by shape, then both light curves would show simultaneous maxima when the broad side of Hektor faces the observer. However, if the light curve is due to albedo patches, then the maximum in reflected sunlight would correspond to the bright or cooler side, which would produce a minimum in the thermal infrared curve. Therefore the two light curves would be correlated in phase if due to elongated shape, but anticorrelated if due primarily to albedo patches.

The amplitudes would also be different in the two cases. If the light curve is due to elongated shape, the amplitude would measure essentially the cross-sectional area exposed (modulated by any minor albedo patchiness). But if an albedo effect dominates in producing the reflected light amplitude, then the amplitude of the infrared light curve would depend on the temperature difference between the markings, and this in turn would depend on the absolute range of albedos. In the case of Hektor this must be very small, since its average albedo is about 2 to 3 percent (*2, 3*). If we assume the albedos of the two hemispheres, with a ratio of 3.1, to be approximately 0.012 and 0.038, then the light absorbed by the different regions of Hektor varies between 0.96 and 0.99, producing a thermal light curve amplitude of only about 1.02:1. (Alternatively, had Hektor been highly reflective—for example, with albedo of 0.86 on one side and 0.28 on the other—the thermal light curve amplitude could exceed 5:1.)

On 4 and 5 April 1979 we obtained new light curves with the 224-cm telescope at Mauna Kea Observatory, when Hektor's brightness was varying by about a factor of 2. The reflected sunlight was represented by photometry at 1.2 μm, and the thermal infrared radiation was represented by photometry at an effective wavelength of 20 μm. Using the known rotation period (*1*), we combined the photometric data from the two nights into a single rotational light curve, shown in Fig. 1.

The primary standard for the 1.2-μm observations was θ Leonis, for which $m_J = 3.34$; the standard for the 20-μm observations was R Hydrae, for which $m_Q = -4.76$. The data in Fig. 1 were obtained in the beam-switching mode with modulation of the asteroid signal against that from the background sky by the standard method of infrared photometry. Each J point is the mean of 240 seconds of integration, and each Q point is the mean of 400 seconds.

Figure 1 establishes that the maxima and minima of the two light curves are correlated, not anticorrelated, and have the same amplitude within the limits of measurement. This, in turn, shows that 624 Hektor must have an elongated shape, which accounts for most of the light variation.

In proposing our model for Hektor (*3*), we pointed out that a compound asteroid consisting of two uniform spheres could not have a light curve amplitude greater than 2:1. Indeed, the original model by Dunlap and Gehrels (*1*) called for a more elongated, cigar-shaped object to explain the observed light curve, which can reach an amplitude of 3.1:1 when Hektor is viewed in its equatorial plane. Therefore we proposed that the crushed material in the contact zone between the two components may be brighter material, analogous to rays around fresh lunar craters. Because of the weak influence of albedo on photometry, this "ray" material would be difficult to detect by photometry alone, but might be spectrophotometrically apparent. At any rate, the material exposed in the side view may be different from that seen in the end views, providing a test of the model. Further, if Hektor formed from two distinct asteroids, the materials seen in the two end views (views of the two original objects) may be different from each other. Since our new results confirm the peculiarity of Hektor's shape and are consistent with our hypothesis (*3*), it is important to follow up with further spectrophotometric observations that might confirm such predicted composition differences.

Interestingly, Jupiter's inner satellite Amalthea was revealed by Voyagers 1 and 2 to be a distinctly Hektor-like object measuring about 155 by 170 by 270 km, or about 83 to 91 percent of the estimated length of Hektor (*6*). In view of its proximity to at least one other small satellite and a ring system of debris, as well as a meteoroid flux enhanced by Jupiter's gravity, Amalthea's collisional history and possible origin as a fragment or a compound object are difficult to assess.

The question of Hektor's origin thus remains puzzling and unresolved, but Hektor may be a fossilized example of the primitive collisional accretion process. In any case, we have established that Hektor is the most elongated object of its size and that it is a worthy candidate for future study or possible spacecraft exploration.

WILLIAM K. HARTMANN
Planetary Science Institute,
Tucson, Arizona 85719
DALE P. CRUIKSHANK
Institute for Astronomy,
University of Hawaii, Honolulu 96822

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Electron Spin Resonance Dating of Animal and Human Bones

Abstract. *Ages of fossil bones were determined by electron spin resonance spectroscopy. The electron spin resonance signal is associated with lattice defects or trapped centers produced by natural radiation in the bones and gives a measure of the total dose of natural radiation, or the archeological dose. Archeological doses were determined for samples of known age from a variety of sites and used to estimate apparent average annual rates of natural radiation at the sites. The method has the advantage that the sample need not be ground or heated, and it should be useful for dating biological materials.*

Natural radiation from uranium, thorium, potassium and their radioactive daughters produces lattice defects or populates existing and radiation-induced electron traps with electrons and holes (*1, 2*). One can determine the total dose of natural radiation, or the archeological dose, from the concentration of defects or traps. Thermoluminescence has been used to obtain the archeological dose, and thermoluminescence dating of potteries and ceramics in archeology has been attempted by several groups (*1, 2*). Jasinska and Niewiadomski (*3*) tried thermoluminescence dating of fossil bones and some biological material; samples exhibited triboluminescence due to defect formation during grinding and chemiluminescence due to oxidation of the residual organic materials during heating.

Electron spin resonance (ESR) of defects or trapped centers produced by natural radiation has been successfully used to estimate the age of the deposits such as stalactites in calcite caves and of min-

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