for which $\epsilon = 0.4°$. Let us take values appropriate to the large satellite of Herculina: $r/d = 5$, $\Delta m/m = (\Delta d/d)^3 = 0.01$, $P = 0.004$ year. Hence $P/\dot{P} = 10^5$ years.

If a satellite were decaying toward the surface of its parent, it would reach there in much less than this characteristic time. Moreover, the orbit would become circular and equatorial in the process, since the tidal forces damp out eccentricity and inclination with roughly the same characteristic time scale. On the other hand, a satellite entirely outside the synchronous orbit would still tend to become coplanar and equatorial but would have increasing eccentricity. Indeed, the eccentricity increase would continue until the escape of the satellite. This is an interesting feature, because satellites of relatively large mass which are evolving toward escape can be used to set an upper limit on the time since the formation of the system, once their current orbits and tidal accelerations are directly measured (for example, by a space telescope). It should be possible with just one or two samples to distinguish between ages for the asteroid belt of more than 10^9 years, as in traditional theories, or less than 10^7 years, as required by the theory of origin which posits a planetary breakup (*7*).

Because the time scale for tidal evolution is proportional to the mass ratio of parent to satellite, it is clear that satellites of small mass (say, 10^{-6} of their parent's mass or less) could not have been appreciably altered by tidal evolution, even over the entire lifetime of the solar system. This condition holds until we consider a satellite size so small that solar radiation pressure becomes an appreciable perturbing force. Clearly, dust size grains and smaller have been completely removed by solar radiation. Nevertheless, large satellites would tidally evolve in a much shorter time scale and we predict that many relatively large, close satellites would now be found lying on the surfaces of their parent minor planets (this prediction implies the existence of many contact binary asteroids).

In view of the small probabilities that observers would be so favorably located or that eight out of the first eight minor planets, which differ greatly in size and type, would all have satellites; and considering their dynamical stability and the lightcurve evidence, we conclude that minor satellites are numerous for each minor planet and are present as the rule, rather than as an exception, among the minor planets.

Note added in proof: The first occultation of a star (SAO 114159) by a minor planet (18 Melpomene) for which an organized effort was made to search for satellites occurred on 11 December 1978. Three photoelectric and several visual timings of the occultation by the parent body were obtained in the Washington-Baltimore area, indicating a 130-km diameter. Additional photoelectric recordings of presumed satellites were obtained from Georgia (50-km diameter) and Pennsylvania (15 km), and visual sightings were reported from California and Arizona. It presently appears that no two observers were located close enough to have seen the same satellite. This seems, nonetheless, to be strong supporting evidence for the generality of the phenomenon.

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1. See *Sky Telescope* **56**, 210 (1978); R. A. Kerr, *Science* **201**, 516 (1978); E. Bowell *et al.*, *Bull. Am. Astron. Soc.* **10**, 594 (1978) (abstr.).
2. The evidence that these occultations do indeed represent satellites of minor planets rather than some other phenomenon consists of the following. Intensity reductions generally correspond to the total occultation of the star's light, rather than to partial occultations as for the rings of Uranus. These reductions are often several magnitudes, and so visual timings by experienced observers can be relied upon. The one large confirmed satellite of Herculina was shown to be comoving through space with Herculina, virtually ruling out a chance alignment of distant asteroids. Ordinary stars near the ecliptic, when monitored photoelectrically, do not show occultation events when not near an asteroid; nor are such secondary events ever seen during lunar occultations. Although most observers have monitored the star for 10 to 20 minutes before and after the occultation, the furthest minor satellite to date was 4 minutes away and the vast majority have been within 1.5 minutes away. At present, we do not know of any viable alternative hypothesis that can explain most of these observations.
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Binary Asteroids: Evidence for Their Existence from Lightcurves

Abstract. *The lightcurves of the asteroids 49 Pales and 171 Ophelia bear a striking resemblance to those of eclipsing binary stars. This evidence suggests that these asteroids are binary objects. Asteroids belonging to the Themis dynamical family have unusual lightcurves, possibly due to satellite events; these unusual lightcurves suggest that multiple objects may be formed during the disruption of asteroids in collisional events.*

Asteroid lightcurves are generally believed to be produced by the rotation of irregularly shaped bodies about their shortest axis. In theory, observations of brightness changes alone do not allow us to distinguish between the rotation of a spotted sphere and an ellipsoid of uniform surface reflectivity (*1*). Nevertheless, numerous investigations of color and albedo variation as a function of rotation have established that color differences over the surfaces of most asteroids are less than 2 percent in the visible region of the spectrum (*2, 3*), the only exceptions known to date being 4 Vesta (*4*) and 944 Hidalgo (*5*).

Such behavior, however, is distinctly uncharacteristic of asteroids in general (*2-4*). Asteroidal surfaces are quite uniform in their colors and albedos, and hence their lightcurves are the result of irregular shape rather than spottedness. It was therefore rather surprising to see the lightcurves displayed in Fig. 1. Physically plausible models consisting of either a spotted sphere or an irregular shape of uniform reflectivity will not produce these lightcurves, especially since surface shadowing can be of little importance because both observations were made at phase angles (Earth-asteroid-sun angle) of less than 3°. Although it is possible that a suitably complex combination of these two models might satisfy the observations, the more straight-forward interpretation is that they are produced by eclipsing binary systems. There are no physical reasons why such systems, once formed, would not be stable. Indeed, Binzel and Van Flandern (*6*) have shown that the gravitational sphere of influence is on the order of 100 times the diameter of the primary body. The rotation period of 49 Pales is 20.8 hours if the successive minima observed by Scaltriti *et al.* (*7*) are separated by one-half rather than one cycle. In this case the lightcurve of Pales (Fig. 1a) is quite similar to that of 171 Ophelia (Fig. 1b) discussed at greater length below. Both lightcurves are indicative of binary systems in that they display essentially constant brightness for slightly more than one-half cycle before fading into Al-

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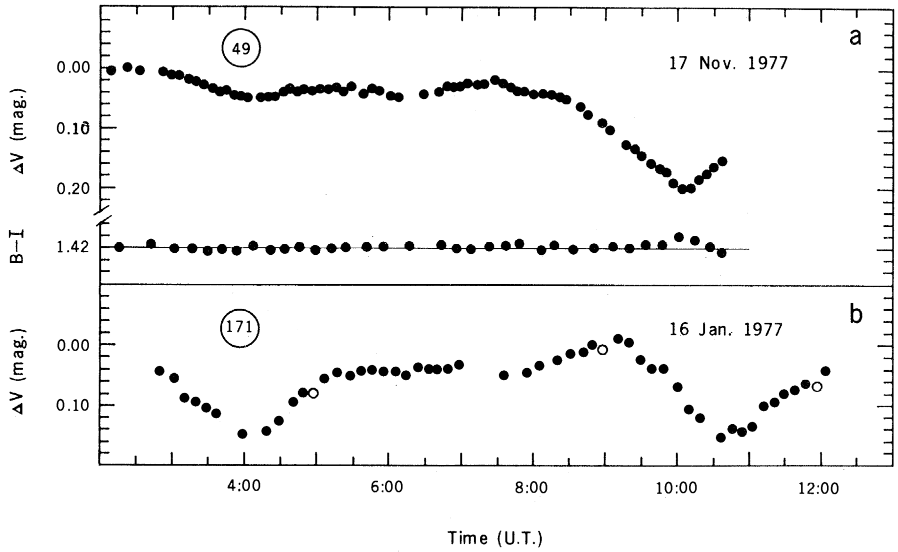

Fig. 1. (a) Lightcurve of the asteroid 49 Pales obtained with the 91-cm reflector and three-channel photometer of Kitt Peak National Observatory. The lightcurve is with respect to a nearby comparison star whose brightness and color were similar to those of the asteroid. The $B - I$ color, that is, the difference in intensity between bands with equivalent wavelengths near 440 nm (B) and 810 nm (I) (expressed in units of magnitude) as a function of time is shown at the bottom. No $(B - I)$ color variation greater than ±0.02 magnitude occurs. (b) Lightcurve of the asteroid 171 Ophelia obtained with a single-channel photometer on the 61-cm reflector of New Mexico State University.

gol-like minima (that is, V-shaped with perhaps flat bottoms). The absence of a change in the relative reflectance between the B (440 nm) and I (810 nm) wavelengths indicates that it is not a color difference which caused the minimum in the Pales lightcurve; that is, the albedo difference between these two wavelengths remains constant. Changes in albedo alone necessary to produce the observed lightcurve with albedo spots would require significant color differences. Since no such differences were observed, the lightcurve cannot be the result of albedo changes over the surface. Ophelia's period is either 6.5 or 13 hours, depending upon whether the minima are separated by one or one-half cycle, respectively. Close examination of the two minima shows that they are different in that the brightness of the one near 4^h U.T. decreases more slowly, and rises more rapidly, than the one near 10^h30^m U.T. The period is therefore probably near 13 hours, with the lightcurve in Fig. 1b representing about 60 percent of a cycle.

Since a binary model with spherical components will account for most features of Ophelia's lightcurve, I will restrict my discussion to a description of such a model. A similar model, although with nonspherical components, also serves to explain the Pales observations. Initially four simplifying assumptions are made, namely, the system consists of two spherical objects with similar albedos in synchronous orbit about one another, the brightness variation being caused entirely by their mutual eclipses. In this case the observed lightcurve is consistent with a system consisting of a primary body and a secondary body whose radii are in the ratio of 1:3 and which orbit about their center of mass in a period of 13 hours, spending approximately 4 hours of each cycle in eclipse. Using these values together with Kepler's third law and the definition of density, I calculate a mean density for these bodies of 1.5 g cm^{-3}. This, however, is a lower limit, for not all the brightness variation can be attributed to mutual eclipses since mutual shadowing, not present in stellar systems, plays an important part, especially at large phase angles, but detectable even at the small phase angle of 3° at which this observation was made. When shadowing and shapes differing slightly from spheres are allowed for, the actual total eclipse duration becomes as small as 3 hours; the period, of course, remains unchanged. The density in this case is 2.8 g cm^{-3}, a value not significantly different from the admittedly crude value of 2.5 g cm^{-3} found for Ceres by Morrison (*8*) using his diameter and Schubart's mass (*9*). The density derived from Ophelia's lightcurve is therefore a realistic one for asteroids. In this model the orbital radius is 3.5 times the radius of the primary body, and hence the probability of observing an eclipse or shadow transit is approximately 40 percent if the orbital planes are randomly oriented. The derived orbital radius keeps both bodies well outside their respective Roche limits; in fact, they would remain intact even if in physical contact (*10*). In reality, both bodies are probably slightly nonspherical and may have minor albedo features which could possibly account for the 4 percent increase in brightness seen in Ophelia's lightcurve near 9^h U.T.

At the time these observations were made, there was no compelling evidence for the existence of asteroidal satellites. In June 1978, however, McMahon reported visual observations of several secondary occultations both before and after successfully observing the occultation of the star SAO (Smithsonian Astrophysical Observatory) 120774 by asteroid 532 Herculina (*11*). An unconfirmed visual observation by Maley about a year earlier had been interpreted by Dunham (*12*) as being a secondary event, but, because the event was not confirmed, this interpretation had not been widely accepted. This time, however, one of the secondary events of Herculina observed by McMahon was also observed simultaneously by Bowell and A'Hearn at Lowell Observatory. Bowell *et al.* (*13*) concluded that the most likely explanation was that a satellite had been detected. Later this same month Christy and Harrington (*14*) announced the discovery of a satellite of Pluto, which is probably in synchronous orbit.

Observations such as these imply that, whatever their mode of origin, binary systems are not uncommon; in particular, the occultation results [discussed in more detail by Binzel and Van Flandern (*6*)] suggest that satellites of asteroids may be commonplace. I believe that we do not see more evidence of this in asteroid lightcurves because of the difficulty of distinguishing photometrically between an elongated object and a close, nearly contact, binary object. Systems of greater separation are easily recognized (Fig. 1) only if a number of rather restrictive conditions are met. Eclipses will be seen only when the orbital plane of the binary object lies near the line of sight; moreover, the larger the orbit, the lower the probability that an eclipse will be seen. Closer systems have a higher probability of being detected, but, if they are too close, their lightcurves become virtually indistinguishable from those produced by the rotation of an elongated object. The larger systems have considerably longer periods and hence require more observing time to detect. Furthermore, these larger systems will be detected only if the secondary object is an appreciable fraction of the size of the primary object, otherwise the resultant change in brightness will not be detectable. For example, although Pluto's eclipses are expected to be deep and narrow, they are detectable only during five or six apparitions around the time of passage of Earth through Pluto's orbital plane (*15*), that is, approximately 4 percent of the time. Even during these favorable apparitions, however, eclipse phenomena are occurring less than 7 percent of the time. It is no wonder then that, whereas we have known Pluto's rotation period for over 20 years (*16*), its rather large satellite has been discovered only recently and from images on photographic plates, and not through lightcurve observations. Herculina's satellite would have been similarly difficult to detect since a brightness drop of 0.10 magnitude may go unnoticed if the primary object is appreciably nonspherical. Nevertheless, now that we know what to look for, it may indeed be possible to detect eclipse events in asteroid lightcurves.

Examples of effects that may be attributable to eclipse events include the following: (i) the contact binarylike lightcurve of 44 Nysa (*17*), (ii) lightcurve maxima sharper than minima seen for 129 Antigone (*18*), (iii) the complex lightcurves seen for 29 Amphitrite (*19*) and 51 Nemausa (*20*), (iv) the lightcurve with triple maxima and minima observed for 1580 Betulia (*21*), (v) the increasing lightcurve amplitude with increasing solar phase angle seen for 349 Dembowska, 354 Eleanora (*22*), and 944 Hidalgo (*5*), and (vi) asteroids such as 532 Herculina (*20, 23*) whose lightcurves show two maxima and minima per cycle at one apparition but only one maximum and one minimum per cycle at another apparition.

Binzel and Van Flandern (*6*) note that binary systems are gravitationally stable for the lifetime of the solar system. Binary systems will be disrupted by collisions, however, on a shorter time scale; thus, few such systems would be primordial. Where do they come from then? I suggest that, whereas at least three of the 13 Themis family asteroids for which I obtained lightcurves show evidence of being binary (*3*), this being a larger proportion than is true of asteroids in general, and since the origin of at least each of the first three Hirayama dynamical families, of which the Themis family is one, from single parent bodies in catastrophic events is well established (*3, 24*), the evidence strongly suggests that the formation of binary asteroids is connected with these catastrophic events. These families are thought to be no more than half the age of the solar system (*25*), and perhaps much younger. Steins (*26*) suggested a lower limit on the age of the Eos family of only 1.5×10^6 years. The escape velocity from the surface of a 150-km spherical asteroid having a density of 3 g cm^{-3} is on the order of 100 m sec^{-1}, whereas the root-mean-square speed of the fragments at the time of disruption has been estimated by Williams (*27*) to be 270 m sec^{-1}. Thus the idea that binary asteroids formed in the relatively recent past during multibody interactions occurring immediately after the catastrophic event which produces an asteroid family is consistent with the known facts.

Binary asteroid pairs could be directly detected through additional occultation observations, space telescope imaging, or interferometric techniques. Additional lightcurve observations at a number of phase angles and at several different apparitions would allow the densities of these binary asteroids to be determined. These observations would provide valuable information, unavailable from any other presently known method, on the bulk properties of asteroids.

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Strain-Softening Instability Model for the San Fernando Earthquake

Abstract. *Changes in the ground elevation observed before and immediately after the 1971 San Fernando, California, earthquake are consistent with a theoretical model in which fault zone rocks are strain-softening after peak stress. The model implies that the slip rate of the fault increased to about 0.1 meter per year near the focus before the earthquake.*

Several precise theoretical models for earthquake instability and associated precursory deformation have recently been proposed. The models that postulate a strain-softening fault zone after peak stress either lack a stress-free ground surface (*1*) and thus are not easily compared with geodetic observations or are for long, vertical, strike-slip faults (*2, 3*) for which few observations have been made. Because the most complete, although still limited, observations for the time before and after an earthquake were those made for the 1971 San Fernando thrust event (*4, 5*), I have formulated a thrust fault version of an earlier strike-slip instability model. The agreement between theoretical and observed values of uplift and earthquake parameters implies that the slip rate of the fault increased near the focus before the earthquake. Aseismic fault slippage before the San Fernando earthquake has been postulated (*4, 6*).

Instability models may be useful for anticipating earthquakes. In theory, the

