where F is the flux from ocean to air, D is the diffusion coefficient, Z is the film thickness, C^w is the concentration of the species in water, and C^w_{eq} is the concentration in equilibrium with the burden in air.

Solubility data for F12 and F11 (*14*) suggest that, if the surface water is in equilibrium with the atmospheric burden, the concentrations of F12 and F11 in water should be about 0.05 and 0.06 ng liter^{-1}, respectively. These concentrations are lower than the measured average concentrations of 0.28 and 0.13 ng liter^{-1}, so it appears that ocean water is supersaturated with F12 and F11. This means that either the solubility data are inaccurate or the water samples were inadvertently contaminated. It is also possible that the ocean surface waters have been contaminated by man-made activities on a global scale. The lowest concentration of F12 and F11 measured, 0.07 ng liter^{-1}, is about what one would expect if the surface water were saturated with F12 and F11. If the surface water were saturated, the ocean would be a relatively ineffective sink for F12 and F11 but could act as a reservoir containing less than 0.5 percent of the atmospheric burden of F12 and F11 in a steady-state situation.

The average surface water concentration for CCl_4 was 0.40 ng liter^{-1}. The flux of CCl_4 into the ocean can be calculated from Eq. 1 with $D = 10^{-5}$ cm^2 sec^{-1}, $Z = 90$ μm, and $S_{CCl_4} = 0.85$. The solubility, S, in seawater is defined as the ratio of the species concentration at the air-sea interface (C^w_{eq}) to the atmospheric concentration at standard temperature and pressure. A high Z is used because CCl_4 is rapidly absorbed in fatty tissues and may be biologically active. For such species the upper limit of the stagnant film thickness calculated from radon data (63 ± 30 μm) is more appropriate. Using Eq. 1, we can calculate a CCl_4 flux into the ocean of 2.8×10^{-16} g cm^{-2} sec^{-1}. If we assume this flux to be typical of all oceans, we obtain an exchange rate of 3.2×10^{10} g year $^{-1}$. The atmospheric burden of CCl_4 from our measurements is calculated as 3.2×10^{12} g. Thus the ocean is a sink for CCl_4 that can provide a turnover rate of 100 years (τ_{CCl_4} = $3.2 \times 10^{12}/3.2 \times 10^{10}$). Our measurements thus indicate that the oceanic sink for CCl_4 is about half as effective as the stratospheric sink.

The surface concentration of CH_3Cl in the Pacific is quite variable (Table 1), with values somewhat higher near the equator. The average surface concentration found was 26.8 ng liter^{-1}. Using an S_{CH_3Cl} of 2.65 (*15*) and other parameters as defined earlier, we estimate a CH_3Cl flux from the ocean to the atmosphere of 2.6×10^{-14} g cm^{-2} sec^{-1}. Extending this to the world ocean body gives an exchange rate of 3.0×10^{12} g year^{-1}. From our measurements, the atmospheric burden of CH_3Cl can be estimated to be 5.5×10^{12} g. Thus, on the basis of our limited data, the ocean appears to be a significant source of CH_3Cl, which can provide an atmospheric turnover rate of about 2 years. This is in reasonable agreement with the estimated CH_3Cl residence time of about 2 to 3 years, due to HO attack (HO = 3×10^5 to 5×10^5 molecules per cubic centimeter).

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Minor Planets: The Discovery of Minor Satellites

Abstract. *The recent confirmation of the discovery of a satellite of the minor planet 532 Herculina indicates that other similar anomalous sightings are probably also due to satellites, which must therefore be numerous and commonplace. There are now 23 candidate satellites for eight minor planets, and no one of these minor planets occulting a star has failed to show evidence of at least one secondary event. Such companions are gravitationally stable but apparently have rapid tidal evolution rates.*

The discovery which led to general recognition of the minor satellite phenomenon (the self-descriptive operational title "minor satellites" is adopted to refer to orbiting satellites of the minor bodies, predominantly the minor planets, in the solar system) was that of J. H. McMahon of 7 June 1978. McMahon responded to a last-minute prediction correction calculated by D. W. Dunham based on astrometric data obtained by W. Penhallow which showed that the path of the occultation of the star SAO (Smithsonian Astrophysical Observatory) 120774 by the minor planet 532 Herculina would cross the western United States. McMahon successfully observed a 20.6-second occultation of the star by Herculina, but he also timed and reported six additional events with durations of 0.5 to 4.0 seconds occurring within 2 minutes before and after the main event (*1*). These secondary events were certainly not atmospheric because the light reduction in each true occultation was nearly four magnitudes.

Table 1. Status of minor satellite observations as of October 1978.

Minor planet	Number of minor satellites: Confirmed	Probable	Suggested
2 Pallas		2	2
3 Juno		1	
6 Hebe		1	
9 Metis			1
12 Victoria			1
129 Antigone		1	
433 Eros		2	2
532 Herculina	1	5	4
Total	1	12	10

Accepting McMahon's observations at face value, Dunham prompted other ob-

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Table 2. Approximate radius of the gravitational sphere of influence (r) as a function of diameter (d) or mass (m) for bodies in the inner solar system.

m (g)	r (km)	d (km)	Comment
2×10^{30}	15,000,000	124,000	
2×10^{27}	1,500,000	12,400	Inner planets
2×10^{24}	150,000	1,240	Largest minor planet
2×10^{21}	15,000	124	Typical minor planet
2×10^{18}	1,500	12.4	Minor satellite
2×10^{15}	150	1.24	Comet?
2×10^{12}	15	0.124	
2×10^{9}	1.5	0.0124	Arizona meteorite?
2×10^{6}	0.15	0.00124	Large meteorite or fireball

servers of the Herculina event to recheck their data for possible secondary events. As a result, a previously overlooked secondary event in nearly perfect agreement with the longest secondary event observed by McMahon was found in the photoelectric record of the occultation made at Lowell Observatory by E. Bowell and M. A'Hearn. These two consistent observations indicated that a secondary body about 50 km in diameter and 1000 km from Herculina (diameter, 220 km) had caused this particular event and was thus the first minor satellite to be confirmed (that is, seen by two or more independent observers).

An investigation of previously observed occultations of stars by minor planets in light of this new discovery shows that minor satellites have been detected before (*2*), often with confusing results. One particularly interesting event occurred on 6 February 1973 when 2 Pallas occulted BD + 2° 2913. Definite occultations of the star by Pallas (approximately 540 km in diameter) were observed in Boulder, Colorado, and Calgary, Alberta, even though their separation perpendicular to the path was 1400 km (*3*). These confusing data can now be explained as due to a minor satellite which occulted the star at Calgary; other puzzling aspects of the event indicate that the star was double.

There are numerous reports of brief occultations that have been seen by observers who were well outside the path of the main occultation events, and these can now be interpreted as due to minor satellites. Such events were observed during the occultation of a star by 129 Antigone in October 1973, SAO 153844 by Pallas on 10 October 1976, and Gamma Ceti by 6 Hebe on 5 March 1977. Dunham proposed that the last of these brief events was due to a satellite (*4*), and the other events were dismissed as being probably spurious. Several momentary occultations reported by observers outside the main path of the 24 January 1975 occultation of Kappa Geminorum by 433 Eros were likewise discarded.

Since the announcement of the confirmed discovery of a satellite of Herculina, the occurrence of secondary events in conjunction with other such occultations has continued. Another occultation of a star by Pallas occurred just 9 days prior to the Herculina event when Pallas occulted SAO 85009. Photoelectric records of the event showed one definite secondary event and possibly two others. [The renowned double star observers W. H. van den Bos and W. S. Finsen reported seeing Pallas as double visually in 1926 (*5*).] Secondary events were also observed when 9 Metis occulted SAO 165132 on 12 July 1978, 3 Juno occulted SAO 144070 on 19 July 1978, 532 Herculina occulted another star on 23 August 1978, and 12 Victoria occulted SAO 161878 on 25 October 1978. Dimming and flickering phenomena around the time of occultation have been reported during three of these events and may be due to swarms of small minor satellites.

Thus, each of eight minor planets that have been observed to occult a star has shown evidence of minor satellites. Table 1 shows the tally as of October 1978. We have also taken note of lightcurve evidence presented by Tedesco (*6*). These observations suggest that minor satellites are both numerous and commonplace.

What is the radius of the sphere of influence for a minor planet, within which it can retain satellites even against solar perturbations? It is proportional to the distance from the sun and to the cube root of the mass ratio. For a "worst case" situation, let the distance from the minor planet to the sun be 1 astronomical unit or 1.5×10^8 km. The typical radii of the spheres of influence for bodies of various masses are given in Table 2, along with the corresponding body diameter d for a density of 2 g cm^{-3}. As a rule of thumb, the radius of the gravitational sphere of influence of a body in the inner solar system (not too near a planet) is roughly 100 times its own diameter. For an object the size of Herculina, the sphere of influence extends to more than 30,000 km. Hence, a minor satellite only 1000 km distant is very stably attached to Herculina gravitationally over the lifetime of the solar system. The collisional lifetime would usually be less than this, depending on size. However, the actual survival limit is most likely to be set by tidal forces, which we will examine next.

Nonrigid gravitating bodies raise tidal bulges on each other, which can result in the conversion of some rotational angular momentum into orbital angular momentum, or vice versa. If the satellite is inside the synchronous orbit (the orbit where parent rotation and satellite revolution periods are the same) and is revolving in the same direction as its parent, the satellite will decay from orbit and the parent's rotation will tend to speed up. The inner martian satellite Phobos is in such a situation and will remain a satellite of Mars only perhaps another 10^8 years. Conversely, a satellite outside the synchronous orbit evolves outward, slowing the parent's rotation, as in the Earth-moon system. At the same time, the eccentricity of the orbit will tend to diminish (the orbit will become circular) in the case of decay or will increase if the satellite evolves outward. The inclination of a satellite to its parent's equator always tends to decrease under the influence of solid body tidal forces. For a satellite of mass Δm revolving about a parent of mass m and density ρ (in grams per cubic centimeter), the radius of the synchronous orbit r_s is related to the parent's diameter d by

$$r_s = 1.87\, P^{2/3} \rho^{1/3} d \qquad (1)$$

where P is the period (in days) for both rotation and revolution. When most of the angular momentum is in the satellite, the pole orientation and rotation period of the parent asteroid will be substantially altered from their original values by the tidal interchange of angular momentum; but, when the reverse is true, it is the satellite's orbit that is subject to the most alteration.

If the satellite's revolution period is P and its time rate of change is $\dot{P}$, then

$$\dot{P} = 0.64 \sin 2\epsilon \left(\frac{\Delta m}{m}\right)\left(\frac{r}{d}\right)^{-5} \qquad (2)$$

where ϵ is the angle by which the tidal bulge leads the satellite and r is the mean distance of the satellite. Equation 2 enables us to estimate a characteristic time scale $P/\dot{P}$ of tidal evolution for a typical minor satellite if we assume that values of ϵ for minor planets are similar to those estimated from the Phobos-Mars case, 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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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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