Volcanic Hotspots on Io: Stability and Longitudinal Distribution

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In the 4 years since the two Voyager encounters, better characterization of the continuing volcanic activity on Io (*1*) has remained a major challenge for planetary astronomers. The spacecraft's thermal measurements were restricted to a snapshot in March 1979, when the Voyager 1 infrared spectrometer (IRIS) scanned approximately 30 percent of Io's surface (*2*). Since that time, infrared observations of Io's eclipses by Jupiter have provided most of our information on volcanic activity and the magnitude of the heat flow (*3, 4*).

Abstract. *We report the first results of a program to determine the longitudinal distribution of volcanic activity on Jupiter's satellite Io. Infrared measurements at 8.7, 10, and 20 micrometers have been taken at a variety of orbital longitudes: strong variation in the 8.7- and 10-micrometer flux with longitude demonstrates that infrared emission arising from volcanic hotspots on Io is strongly concentrated in a few locations. Analysis of these data suggests that the active volcanic regions observed by the Voyager experimenters are still active, particularly the region around the feature known as Loki. Another source of flux, although of somewhat smaller magnitude, is indicated on the opposite hemisphere. If these sources are the only major volcanic centers on Io, then current global heat flow estimates must be revised downward. However, heat flow from as yet unobserved longitudes, hotspots at high latitudes, and conducted heat flow must still be measured.*

During an eclipse, there is no reflected solar radiation from Io to be confused with intrinsic thermal emission. When surface heating by solar insolation ceases, the ambient surface temperature drops, increasing the relative contribution of the volcanic hotspots to the total spectrum. Under these conditions, the emission spectrum of the hotspots can be determined with some precision. However, the eclipse data are always restricted to the same hemisphere of Io and, when geometric projection is considered, the conclusions drawn pertain to a limited region. On the other hand, monitoring of Io at 5-μm wavelength has provided information about short-lived (several hours to days), high-temperature sources (~600 K) (*5, 6*), but these are small and intermittent; they do not contribute much to the mean heat flow from Io (*4, 6*).

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Io's heat flow can be measured by remote sensing, either from a spacecraft or from Earth, because much of the power escaping from the interior is channeled into volcanic hotspots that occupy a very small fraction of the surface. Hotspot temperatures are hundreds of degrees higher than the ambient surface, which enables their contribution to the total emission spectrum to be distinguished. All estimates of Io's heat flow depend on remote measurements of this spectral signature. These estimates are lower limits since global conductive heat flow (radiated to space at near the ambient temperature) is not detected. Previous estimates of Io's heat flow have raised a number of important questions (*3, 4, 7*). The estimated values of between 6 and 8 × 10^{13} W (or 1.5 to 2.0 W m^{-2}) require much more power than can be supplied by radioactive heating and support the suggestion of Peale *et al.* (*1*) that tidal heating is the major source of internal energy for Io. Detailed attempts to model the tidal energy input, however, have resulted in values that are still less than about half of these heat flow estimates (*8*).

There are two noteworthy limitations to previous heat flow estimates. First, as remarked above, the Voyager data and the ground-based estimates refer to a relatively narrow range of longitudes on Io, primarily between about 270°W and 360°W. In estimating total emitted thermal power, all investigators have assumed that the unobserved regions of Io emit the same average power as do the observed areas. Second, the observations span only a very brief period compared with typical time scales for volcanic phenomena on Earth. Thus, to characterize Ionian volcanism both temporally and spatially, measurements must be made at all longitudes and continued for a long period of time. It is particularly important that these observations be made now so that Io's thermal state during the 1988–1990 Galileo mission can be related to the Voyager observations and the volcanic chronology over the intervening decade.

Io's heat flow can be monitored telescopically at essentially all longitudes by using a technique that relies on the observation of a small region of the infrared spectrum. In this region, flux from the hotspots dominates both the reflected solar radiation and the ambient thermal emission from approximately 99 percent of the surface, which is in equilibrium with insolation. Figure 1 shows the infrared spectrum of Io and identifies the region where hotspot emission is most important. Reflected sunlight is the major component for all wavelengths short of about 6 μm. At wavelengths less than 4 μm all of the thermal emission from Io is negligible compared with the reflected component; at wavelengths longer than 10 μm, the dominant source is background emission. However, between 6 and 10 μm, emission from Io's hotspots provides most of the radiation. It is from measurements in this part of the spectrum that we now derive new information about Io's volcanism and total heat flow (*9*).

Longitudinal Heat Flux

Our infrared observations were obtained with NASA's 3-m infrared telescope facility (IRTF) on Mauna Kea. Most of the data reported here were obtained during the 1983 apparition of Jupiter. In addition, we include in our analysis several unpublished observations taken with the same system by W. M. Sinton (6 March 1983) and R.M.N.

and A. Tokunaga (18 February 1983) and an earlier eclipse observation by D.M. and C. M. Telesco (Fig. 2). All the observations were made with the IRTF bolometer and filter set following the usual IRTF observing procedures (*10*). The primary standard star for most observations was Alpha Boötes, which was near Jupiter. Observed magnitudes were corrected for atmospheric extinction and reduced to flux (*11*). The data were taken through three filters: an 8.7-μm narrow-band filter (~1-μm full width at half maximum) and the two standard broad-band 10-μm (N) and 20-μm (Q) filters (*12*).

Infrared flux at 8.7, 10, and 20 μm is plotted as a function of orbital longitude in Fig. 2. The data clearly show that the amplitude of flux variation with longitude is much larger at 8.7 and 10 μm than at 20 μm, as expected if the major source of variation is the changing contributions from a few, discrete hotspots (see Fig. 1). Also, the general agreement of our new data with measurements taken months and even years earlier suggests that the basic emission characteristics have remained relatively constant during the period covered by the observations. The peak emission at 8.7 and 10 μm occurs near longitude 300°W—this is approximately the center of the darker, red hemisphere observed well by Voyager's imaging and IRIS experiments. However, the peak is at a longitude significantly different from those sampled by eclipse observations (~20° either side of 0°W). The most prominent hotspot observed by IRIS, the Loki area (13°N, 310°W), is also located in the center of this hemisphere. In 1979 Loki by itself accounted for a substantial fraction of the total emission observed by IRIS (*2*), and our observations suggest that this volcanic center is still active.

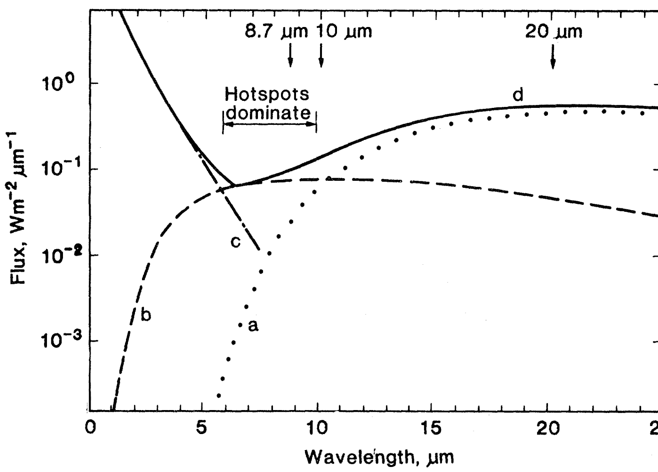

Fig. 1. Io's spectral radiance and its components as a function of wavelength: (curve a) thermal emission from the passive, insolation-heated, surface of Io (taken as an average disk temperature of 129 K); (curve b) thermal emission from the hotspots (disk centered at longitude 300°W calculated from observed Voyager hotspots as discussed in the text); (curve c) reflected sunlight (*21*); and (curve d) the sum of the components. The horizontal arrows mark the wavelength range where emission from the hotspots dominates the spectrum. The vertical arrows mark the effective wavelengths for the data presented in this paper.

Surface Hotspot Models

In order to determine the characteristics of the hotspot sources responsible for the observed emission and the implications for global heat flow, we first examined the background thermal emission from the bulk of Io's surface, which is in solar equilibrium. Then we calculated the emission from the hotspots observed by Voyager in 1979. Finally, we estimated the minimum change in the Voyager hotspots necessary to satisfy the 1983 data.

Background emission. We have modeled the background thermal emission by using the blackbody emission for an average disk temperature for Io at each longitude. The Bond albedo for each longitude was determined from published light-curve data and the best estimates of the required photometric and geometric parameters (*13*). Our model is less complex than the spherical models used for asteroid and satellite radiometry. However, the variation due to changing albedo with longitude is well modeled by this approximation. Comparisons with the current asteroid radiometry models show that errors in the predicted absolute flux from the single disk temperature model are less than about 25 percent at 10 μm and less than that at 8.7 μm (*14*). This is well within the uncertainty in determining the actual albedo, emissivity, and other thermal parameters for Io, and the magnitude of this uncertainty is far less than the magnitude of the longitude effects seen in the data. The emissions calculated from the background model are plotted as curves a in Fig. 2. At 20 μm, all the radiation we observe is background radiation, which matches the flux predicted by the background model (*15*). At 8.7 and 10 μm the predicted flux falls well below the data, and the albedo variation fails entirely to explain the observed variation, as expected.

Predictions from Voyager's data. Given the agreement in the longitude of peak flux with a major volcanic center, we have chosen to begin our analysis by seeing what the predicted flux would be from the hotspots Voyager observed if all of them were still active. Using the basic parameters of location, effective area, and temperature of each source, which was characterized by analysis of Voyager IRIS data (*2*), we have calculated values of flux shown in curves b of Fig. 2 (*16*). The curves are a prediction of what our observations should have shown had we performed the experiment in 1979. However, while the hemisphere containing the Loki and Pele sources was reasonably well covered by the IRIS investigation, the region on the trailing hemisphere was not mapped for hotspots. Also, there may be rather large uncertainties in the areas assigned to the smaller spots and in the characteristics of regions where IRIS detected enhanced emission without an obvious spot being seen. We have not attempted to account for these uncertainties here (*17*). The comparison with the data shows that the longitudes associated with the Loki volcanism are still responsible for most of the emission in the peak. The general level of emission implied by our data is higher than predicted by the Voyager model for the Loki region. Some additional hotspot emission also appears to be required from the leading hemisphere, centered near 100°W.

The current model. Since the prediction from the Voyager model is in rough agreement with the observations, we have elected to find the minimum changes required to the Voyager model to make it consistent with the 1983 data rather than perform an unconstrained multiparameter fit to the data. In order to match the peak flux near 300°W we must increase the emission from the region of Loki. This is justified by the close agreement in longitude between Loki and the flux peak and by the suggestion that the sources may be long lived. Curves c in Fig. 2 illustrate a model where we have matched the flux by elevating the temperature of the larger component of Loki to 290 K, 45 K greater than reported by Pearl and Sinton (*18*).

The emission in the leading hemisphere was matched by assuming a source equal to the size of Loki centered at 100°W or an equivalent grouping of sources with a fairly narrow longitude range and the same total area. The temperature required to match the flux at 8.7 μm is 260 K, in the same range as the hotspots measured by Voyager. In addition to the assumption of hotspots and the background model, this approach effectively uses three independent parameters—the temperature of Loki, the location of the new spot, and its temperature (assuming the same area as Loki). Clearly, the agreement with the data is good, particularly at 8.7 μm (*19*).

Obviously, alternative models are possible. For instance, a smaller increase in the flux from the Loki region would be needed if the background model were increased at the shorter wavelengths by the addition of a low albedo component with somewhat higher temperature than the average. In that case, however, it becomes harder to match the entire infrared spectrum, especially the data at 20 μm, with the model.

The data also indicate some interesting problems for future observations to solve. These problems include whether further sources will be required when the missing longitude ranges are observed, how large the temporal variations are from year to year, and further refinement of the longitude of the main source, which the data at 10 μm suggests is somewhat to the east of Loki. Nevertheless, the existing data greatly improves our understanding of Io's heat flow.

New heat flow estimates. Our observations show that an important assumption of previous heat flow estimates, namely homogeneity of the hotspot distribution, is not justified. Despite any systematic problems of modeling, the observations clearly show that about twice as much infrared radiation is coming from hotspots on one side of Io as from the other. We must therefore examine the new limits that can be set on the global heat flow estimates based on this new knowledge.

A conservative approach is to calculate the power radiated by only those hotspots observed or modeled, neglecting any unobserved contributions. The hotspots Voyager observed radiate $\sim 2 \times 10^{13}$ W (or ~ 0.5 W m^{-2} if averaged over Io's surface), and half of the flux in this model is being supplied by Loki alone. The same calculation with our new model yields 4.2×10^{13} W (or ~ 1.0 W m^{-2}). We believe this constitutes a reasonable lower limit to the current global heat flow, but we must also account for contributions from unobserved longitudes. As another limitation, we find that the data are (marginally) consistent with another source equal to our new hotspot but centered at 180°W; this would result in a total of 5.6×10^{13} W (1.35 W m^{-2}). Thus our estimate based only on longitudinal distribution is that the observable hotspots contribute between 4 and 6×10^{13} W at the current time.

Heat flow from high latitudes, poorly observed from either Voyager or from the ground, must also be taken into account. Geologically, the polar regions of Io are quite distinct from the equatorial area; however, numerous calderas and other volcanic features are seen in Voyager images of the southern polar regions. At least some of the polar volcanism may be of the high-energy, short-lived variety suggested by McEwen and Soderblom (*20*). These may not contribute much to heat flow, but we cannot rule out the possibility of significant hotspot activity in some polar areas. If we assume that the hotspot emission is uniformly distributed with latitude, we arrive at a value of $\sim 5 \times 10^{13}$ W for the global average. If the average high-latitude volcanic activity were more like that in the Loki region, then the heat flow would be higher. Further telescopic observations of all longitudes and, ultimately, data from high latitudes, possibly from the Galileo spacecraft, will be needed to completely determine Io's heat flow from volcanic hotspots.

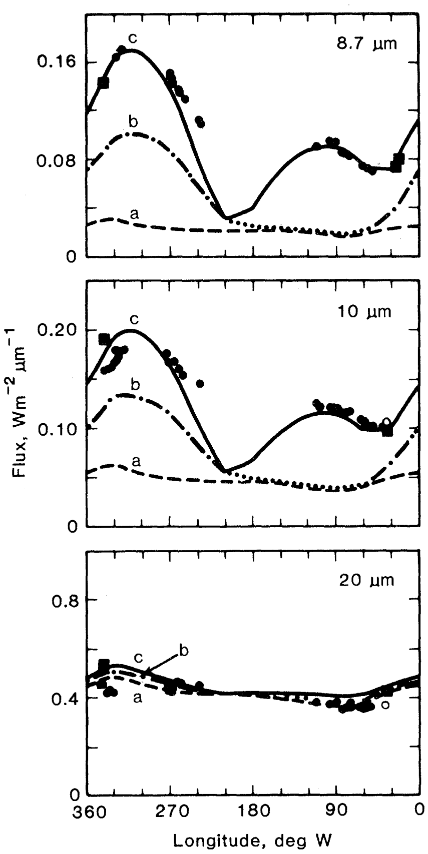

Fig. 2. Comparison of observations and models. Plots of Io's disk-averaged spectral flux as a function of the center-of-disk longitude. The closed circles plot our new observations (*22*); solid squares mark data supplied by W. Sinton; the open circles mark the data of Morrison and Telesco (*3*). The curves show the results of three model calculations: (curves a) thermal emission expected from insolation heating alone (taking into account Io's albedo distribution (*13*); (curves b) dependence expected from the hotspots observed by Voyager; and (curves c) plot for our current model. The dotted segment of curves b indicates large uncertainties due to regions of Io not well observed by Voyager. The upper and middle frames refer to the spectral range where hotspot emission dominates, whereas the 20-μm plot in the bottom frame is at a wavelength where the thermal emission is dominated by insolation heating.

Conclusions

By observing the infrared flux at 8.7, 10, and 20 μm simultaneously we have been able to measure the infrared emission from volcanic hotspots on Io's surface as a function of longitude. Using the first data from this program we can draw a number of significant conclusions about the nature of Io's volcanism and place new limits on Io's global heat flow.

1) Volcanic hotspots are not distributed uniformly in longitude; the hemisphere containing Loki contributes the bulk of the infrared emission at wavelengths consistent with a hotspot origin.

2) Our observations combined with Voyager data indicate that most of the heat from Io's volcanic interior escapes through a relatively small number of major volcanic centers.

3) The primary volcanic center at present is most probably associated with Loki, the main center of activity identified by Voyager 4 years ago. This suggests that Io's volcanism may be deep-seated and persistent.

4) Any estimate of the actual global average heat flow from Io still remains tied to assumptions about the spatial distribution of hotspots. If the two major regions identified in our data are the only important emitting regions, then the total heat flow may be about half that previously estimated. However, heat flowing from the polar regions and from as yet unobserved longitudes and heat conducted through the passive surface must still be measured.

References and Notes

1. S. J. Peale *et al.*, *Science* **203**, 892 (1979); B. A. Smith *et al.*, *ibid.* **204**, 951 (1979); L. Morabito *et al.*, *ibid.*, p. 972.
2. R. Hanel *et al.*, *ibid.* **204**, 972 (1979); J. Pearl and W. M. Sinton, in *Satellites of Jupiter*, D. Morrison, Ed. (Univ. of Arizona Press, Tucson, 1982), pp. 724–756.

3. W. M. Sinton, A. T. Tokunaga, E. E. Becklin, I. Gatley, T. J. Lee, C. J. Lonsdale, *Science* **210**, 1015 (1980); D. Morrison and C. M. Telesco, *Icarus* **44**, 226 (1980).
4. D. L. Matson, G. A. Ransford, T. V. Johnson, *J. Geophys. Res.* **86**, 1664 (1981). Using both eclipse and spectral data, Matson *et al.* made the first estimate of total heat flow from Io's hotspots and showed that anomalous emission has been occurring for at least a decade.
5. F. C. Witteborn *et al.*, *Science* **203**, 643 (1979); W. M. Sinton *Astrophys. J.* **235**, L49 (1980).
6. W. M. Sinton *et al.*, *Icarus* **54**, 133 (1983).
7. W. M. Sinton, *J. Geophys. Res.* **86**, 3122 (1981).
8. C. F. Yoder and S. J. Peale, *Icarus* **47**, 1 (1981); P. J. Cassen *et al.*, in *Satellites of Jupiter*, D. Morrison, Ed. (Univ. of Arizona Press, Tucson, 1982), pp. 93–128.
9. The principle of using spectral information to separate the hotspot and background components was used by Matson *et al.* (*4*) and Sinton (*7*) in their estimates of heat flow, but no longitude coverage was available for their analyses.
10. Data were taken using a 6- or 8-arcsec aperture in the standard chopping mode of infrared photometry. The aperture size was chosen so that a 6-arcsec aperture was used when seeing was 2-arcsec or less and the 8-arcsec aperture was used during the infrequent times when seeing was 2 to 3 arcsec. The chopper throw was 8 arcsec when the 6-arcsec aperture was being used and 10 arcsec when the 8-arcsec aperture was used. At all times the chopping direction was oriented perpendicular to the line that joined the satellite and Jupiter.
11. The primary standard for the infrared photometry was Alpha Boötes. The relative magnitude of Alpha Boötes and the flux density corresponding to zero magnitude derives from the Alpha-Lyrae–based magnitude system in A. Tokunaga, *Astron. J.* **89**, 172 (1984): 1.16×10^{-16} W cm^{-2} μm^{-1} at 10.0 μm and 7.4×10^{-18} W cm^{-2} μm^{-1} at 20.0 μm. An extrapolation using a 9400 K blackbody flux distribution (consistent with Tokunaga's calibration) was used to obtain the flux densities of zero magnitude at 8.7 μm.
12. Data taken in the broad band-passes were corrected to monochromatic flux densities using the known filter characteristics and estimates of the effects of telluric water on the atmospheric transmission. Estimates of the amount of precipitable water vapor in one air mass were made using average values at Mauna Kea of 1 mm/air mass on relatively dry nights and 5 mm/air mass on wet nights. The judgment of a wet or dry night was made on the basis of relative humidity readings at the observatory, the 10 μm/20 μm flux ratio for the standard star, and the extinction coefficient derived from 20-μm observations of the standard star.
13. D. Morrison and N. D. Morrison, in *Planetary Satellites*, J. A. Burns, Ed. (Univ. of Arizona Press, Tucson, 1977), pp. 363–378; radius assumed was 1815 km [M. E. Davies and F. Y. Katayama, *J. Geophys. Res.* **86**, 8635 (1981)]; average geometric albedo = 0.6; phase integral q = 0.9 [D. Morrison, in *Planetary Satellites*, J. A. Burns, Ed. (University of Arizona Press, Tucson, 1977), p. 269]. Two major uncertainties in modeling the background flux are the value of the Bond albedo (D. Simonelli and J. Veverka, *Icarus*, in press) and the variation of brightness temperature with wavelength [D. L. Matson *et al.*, *Bull. Am. Astron. Soc.* **15**, 852 (1983)]. The amount of low albedo material on the surface will also affect the background spectrum since these areas will be warmer than the model for the average disk used here. However, the exact percentage of such dark surface is not known nor the fraction of such areas which are heated chiefly by volcanic activity rather than insolation. Variations in these properties may change the estimates of the extra hotspot flux needed to fit the short wavelength data but will not affect the conclusions about the general pattern of hotspot distribution.
14. R. H. Brown *et al.*, *Icarus* **52**, 188 (1982).
15. This is in agreement with the 20-μm data of D. Morrison, in *Planetary Satellites*, J. A. Burns, Ed. (Univ. of Arizona Press, Tucson, 1977), pp. 269–301.
16. For each longitude the model calculates the total emission spectrum from Io, using the projected areas of each hotspot and summing the flux from that spot with that from the ambient background and the other hotspots [see also (*7*)].
17. J. Pearl, personal communication.
18. The same flux levels could also be modeled by increasing the area of volcanic material exposed in the Loki region. For instance, a region just north of Loki, Amaterasu Patera, was not measured by the IRIS but has albedo and color characteristics similar to other Voyager hotspots (A. McEwen, personal communication). If this region has a temperature of 400 to 450 K, the same results shown in curves c of Fig. 2 can be obtained for these three wavelengths with no change in Loki itself. This is not an exact equivalence. Further observations and analyses of data at other wavelengths may be able to constrain these models more tightly.
19. The general distribution of hotspots suggested here is consistent with the 5-μm variation with longitude reported by Sinton *et al.* (*6*), although the 5-μm pattern is confused by the variations in reflected sunlight (Fig. 1) and the time variability of the small hot sources. Also, as expected from our data, thermal emission from Io is higher at eclipse disappearances than at reappearances [D. Morrison and D. P. Cruikshank, *Icarus* **18**, 224 (1973)], suggesting more hotspot activity in the trailing hemisphere generally [W. M. Sinton *et al.*, *Bull. Am. Astron. Soc.* **15**, 851 (1983)].
20. A. S. McEwen and L. A. Soderblom, *Icarus* **55**, 191 (1983).
21. The actual near infrared spectrum is complicated both by the time variable contributions from small hot sources (*6*) and by absorbtion features in the reflected sunlight [see G. T. Sill and R. N. Clark, in *Satellites of Jupiter*, D. Morrison, Ed., (Univ. of Arizona Press, Tucson, 1982), pp. 174–212].
22. The orbital phase coverage for Io is summarized as follows: 50 to 64 deg. 19 July, 74 to 111 deg. 21 July, 235 to 271 deg. 20 July, 316 to 328 deg. 18 February, 326 to 340 deg. 7 August 1983 [UT]. Additional phase coverage was obtained from the following sources: 35 deg. 12 April 1980, D. Morrison and C. M. Telesco in (*3*); 36 deg. 24 April 1981, W. M. Sinton in (*3*); and 339 deg. 6 March 1983, W. M. Sinton in (*6*).
23. We thank John Pearl for a critical review and several helpful suggestions for improvements. We also thank Alan Tokunaga, who worked with us to prepare the plans for this program and helped acquire some of the data, C. Kaminski for his help with the telescope and equipment, and W. Sinton for allowing us to use some of his recent data in advance of publication. Martha Hanner shared valuable telescope time from another program, allowing us to acquire some of our coverage. A portion of this work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract to NASA.

RESEARCH ARTICLE

The Precursor of the Cretaceous-Tertiary Boundary Clays at Stevns Klint, Denmark, and DSDP Hole 465A

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The mass extinction of organisms at the end of the Cretaceous, about 65 million years ago, has given rise to numerous hypotheses. In 1979 a new catastrophic hypothesis to explain this extinction was proposed by Alvarez *et al.* (*1*). They suggested that an Apollo asteroid about 10 km in diameter collided with Earth and that the dust ejected from the impact reached the stratosphere and caused both temperature changes and darkness lasting several months; this event would have suppressed photosynthesis and led to the collapse of most food chains (*1, 2*). The first chemical evidence for such an impact was the discovery of anomalously high concentrations of iridium and other platinid and siderophile elements in Cretaceous-Tertiary (K/T) marine boundary clay-rich layers, both at Stevns Klint, Denmark, and in the Umbrian Apennines, near Gubbio, Italy (*3, 4*). These elements are generally depleted in Earth's crust relative to their cosmic abundances. The observed iridium concentrations at the above localities were 160 and 30 times, respectively, the average terrestrial concentration. Since then, similar geochemical anomalies have been determined by researchers at several laboratories in marine and nonmarine sediments at K/T boundary layers, recovered from more than 50 sites around the world. (*5–10*). These results were recently summarized by Alvarez *et al.* (*2*).

At present, the impact of a large extraterrestrial object, a chondritic meteorite, is widely accepted as the most plausible explanation for the worldwide iridium anomaly at the end of the Cretaceous (*2, 5, 8, 10–14*). It remains to be established whether the biological extinction and the

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