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23. This work was supported in part by the Fondo de Investigaciones Sanitarias and the Comisión Asesora para la Investigación Científica y Técnica.

19 March 1985; accepted 17 December 1985

The Discovery of Dust Trails in the Orbits of Periodic Comets

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Analysis of data from the Infrared Astronomical Satellite has yielded evidence for narrow trails of dust coincident with the orbits of periodic comets Tempel 2, Encke, and Gunn. Dust was found both ahead of and behind the orbital positions of these comets. This dust was produced by the low-velocity ejection of large particles during perihelion passage. More than 100 additional dust trails are suggested by the data, almost all near the detection limits of the satellite. Many of these dust trails may be derived from previously unobserved comets.

THE INFRARED ASTRONOMICAL SATellite (IRAS) was launched on 26 January 1983 with the primary mission of mapping the sky at thermal infrared wavelengths and making observations while pointed toward particular objects of astrophysical interest (*1*). Four broad-band filters, having effective wavelengths of 12, 25, 60, and 100 μm, were used. IRAS was placed into a near-polar orbit whose plane was perpendicular to the Earth-sun line. As it orbited Earth every 103 minutes, its array of detectors swept out a strip 0.5° wide on the sky. The orbital precession rate of ~1° per day maintained the Earth-sun-satellite angle of ~90°. "Looking" straight out from Earth, IRAS would have mapped most of the sky in 6 months. To increase the rate of sky coverage, the orientation of IRAS was continually shifted by 0.25° in ecliptic longitude from orbit to orbit (*2*). This shifted the image of the sky by half the width of the detector array on each successive orbit. Consequently, the same location of sky was observed twice, over two consecutive orbits. This was designated as an "hours-confirmed" observation or HCON.

The mission was structured so that increasing ecliptic longitudes were observed over a period of about a week, and then the same region of the sky was rescanned the following week. This pattern was maintained over the first 7 months of the mission so that a given sky location was observed a total of four times. The first week and second week periods were designated the first and second HCON's, respectively. Over the remaining 3 months of the mission, a third HCON was obtained over most of the sky.

The observational strategy allowed for the study of extended solar system structures, such as the zodiacal emission, and also allowed for parallactic observations of solar system objects with Earth's orbital diameter, or a portion thereof, used as a baseline. This procedure was necessary to identify and accurately model the extended emission from solar system dust. The accurate study of extended emission from sources beyond the solar system (such as the galactic cirrus) requires that the effects of solar system dust be removed.

The final data products included three sets of sky flux maps, corresponding to the three HCON's, in which the sky was divided into 212 plates measuring 16.5° on a side (to allow for some overlap). These plates were constructed by pasting together individual scans of the sky from a given HCON and binning them into pixels ~2 arc minutes square (*3*). Typically, the scans used were taken over a period of weeks.

While analyzing the IRAS sky flux maps generated from the first HCON, we found trails of dust extending across many of the 16.5° plates. These trails appeared to be very narrow (a few pixels or less) and linear. Some extended completely across the plates, but most were shorter, on the order of 10° or less in apparent length. Two of the brightest trails (Fig. 1) were found to coincide with the projection on the sky of the orbits of comets Tempel 2 and Encke. A fainter trail contained comet Gunn (Fig. 2).

Jaggedness and breaks in the trails are due to data binning and changes in viewing from scan to scan. The greater the time between adjacent scans within a plate, the greater the parallax of the trail orbits. Thus, across some plates a trail may appear to break and to be angularly displaced.

The trails were identified by visual inspection of the lower bits of many of the first HCON images, without the benefit of spatial filtering (which, when properly tuned, would greatly enhance their contrast). The surface brightness of these trails was comparable to or much less than scan-to-scan variations in background brightness. This was also true with respect to noise levels in-scan. The fact that the dust trails were seen, in most cases, is due to the ease with which the eye can pick out a line of weak signal in an otherwise noisy image.

Determining the precise instantaneous length of a dust trail is hampered by the restricted viewing geometry (solar elongation ~90° ± 30°) and by the motion of the dust particles that make up the trails in their orbits over the period covered by the scans that compose an individual plate. Over a period of weeks, dust trail particles may have moved several degrees. Since scans generally cover increasing longitudes with time, dust trails with particles moving in prograde orbits may appear artificially elongated on

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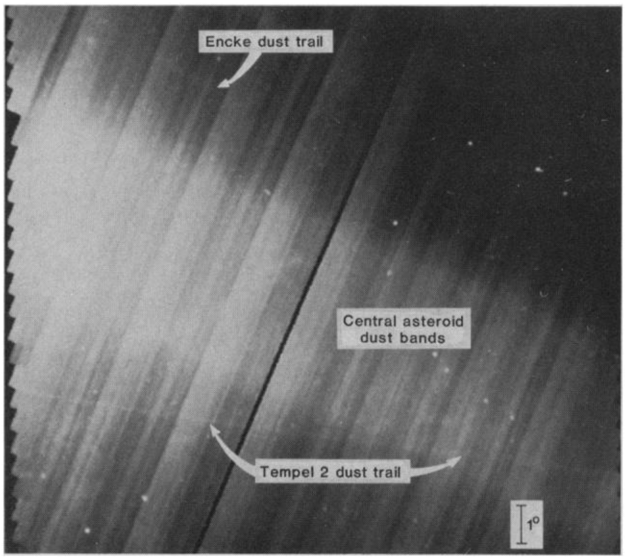

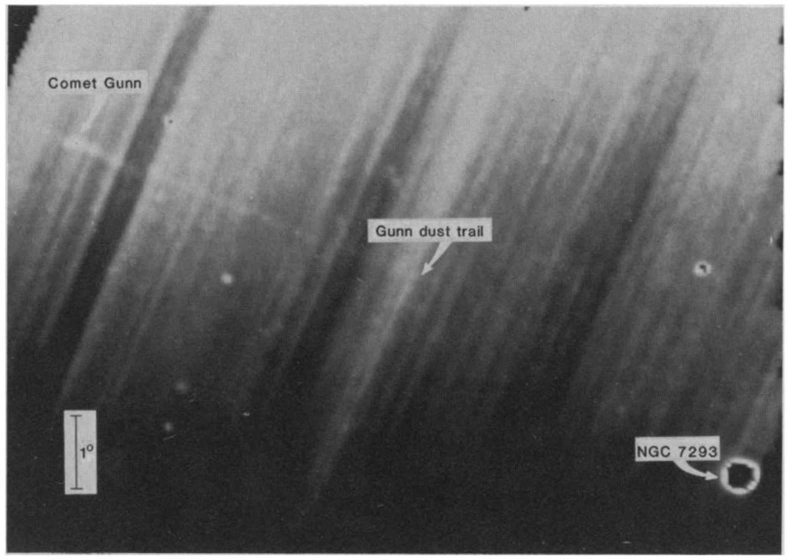

Fig. 1 (left). A 60-μm image of the ecliptic plane. North is at the top, and east is to the left. The wide band cutting across the image is the central asteroid dust band, which straddles the ecliptic and consists of asteroid collision debris (*13*). The Encke dust trail is to the north of the ecliptic, having passed through its ascending node. The Tempel 2 dust trail is to the south of the ecliptic, extends across the plate, and is seen just after passing through its descending node. The image is made up of scans taken between 19 June and 28 June 1983. Over this time interval, comet Tempel 2 moved from ~2.5° to 9° eastward beyond the plate boundary, while comet Encke moved from ~0° to 2.5° eastward from the plate boundary. Wispy structures seen throughout the fields are galactic cirrus. The plate center coordinates are 0^h right ascension and 0° declination (1950), geocentric. Fig. 2 (right). A 60-μm image of comet Gunn and the Gunn dust trail. North is at the top and east is to the left. The dust coma of the comet is clearly visible in the upper left, and the faint continuation of the dust trail can be observed ahead of the comet's orbital position. The large planetary nebula NGC 7293 is visible in the lower right corner. The image is made up of scans taken between 26 May and 8 June 1983. The plate center coordinates are 22.7^h right ascension and −18.7° declination (1950), geocentric.

the sky flux maps. Also, some trails may be arbitrarily truncated at a plate boundary and are not picked up again on another plate. Particularly interesting segments (such as just ahead of or behind the orbital position of the source comet) may not have been observed. With these restrictions in mind, however, we can estimate the minimum lengths of the dust trails and their approximate relation to the orbital position of the parent comet.

Fortunately, the above constraints do not substantially impede dust trail identification with known comets. We accomplished this identification by comparing dust trail positions with projected comet orbits. Of the dust trails we have labeled, comet orbits were found whose projections, over the time interval spanned by the plate, matched each trail.

By far, the brightest dust trail at the time of the IRAS mission was that associated with the orbit of comet Tempel 2. We observed it at 12, 25, and 60 μm, and weakly at 100 μm. Traversing more than seven contiguous 16.5° plates in the first HCON, the Tempel 2 dust trail extended at least 8° behind and 4° ahead of the comet's orbital position in mean anomaly. This corresponded to a length of more than 1/2 AU at the comet. During the time spanned by the scans of Fig. 1 (late June), the trail appeared over 48° of the sky as seen from Earth. Viewing geometry and dilution by the much brighter galactic plane restricted the visibility of a portion of the continuous trail. There was, however, some attenuation away from the comet's orbital position, and the trail was not obvious at locations 8° ahead of and 15° behind Tempel 2 in mean anomaly.

The Tempel 2 dust trail was uniformly narrow, never more than ~4 arc minutes in projected width perpendicular to the line of sight (*4*). When comets are observed at visible wavelengths, sometimes an antitail will be seen as Earth passes through the orbital plane and a viewer sees an edge-on view of material that is distributed in that plane. After Earth passes through the plane, the antitail becomes increasingly diffuse and soon disappears. We considered the possibility that a similar effect might be associated with the dust trails. However, on 23 May 1983, the Tempel 2 trail was observed at a viewing angle of 12° (*5*) and was later observed as Earth passed through its orbital plane on 22 July. Throughout, there was no suggestion of any diffusion into the orbital plane. There was also no obvious deviation of the trail from the projected orbit of the comet. This lack of deviation indicates that dust trails are actually debris distributed along and confined to the orbit of the parent body.

After the IRAS mission, a 10° tail was reported to have been observed by IRAS as a series of point sources at 25 μm (*6*). This tail was thought to be due to the low-velocity emission of large particles whose relative motion was under the influence of radiation pressure (*7*). Comparison with the sky flux maps showed that the "anomalous tail" was actually a segment of the Tempel 2 dust trail.

The narrowness of each of the comet-associated dust trails and the fact that material is seen both ahead of and behind the comet in its orbit indicates that a substantial component of large particles, little affected by radiation pressure, is ejected at low velocities (meters per second) in arbitrary directions. These particles assume orbits nearly identical to that of the parent comet, some with slightly larger and others with smaller orbital speeds. Their orbital phases are thus dispersed about that of the parent comet.

Upper limits of the surface brightness densities for a bright segment of the Tempel 2 dust trail at the effective wavelengths of the IRAS broad-band filters (12, 25, 60, and 100 μm) were estimated at 2×10^5, 4×10^5, 2×10^5, and 10^5 Jy/sr, respectively. These densities correspond to an optical depth of $\sim 10^{-8}$, comparable to the asteroidal dust bands (*8*). Assuming submillimeter-sized particles (a lower limit, since much smaller particles will not emit efficiently at 60 μm), we calculated a maximum particle density of $\sim 10^{-11}$ cm^{-2}, or one particle in a box that is 50 m on a side. Over the length of the observed trail (1/2 AU), this translates to a minimum mass of $\sim 10^{12}$ g.

The Gunn dust trail (Fig. 2) was observed past perihelion at a solar distance of 2.7 AU. The trail was weakly seen at 12, 25, and 60 μm, and was virtually nonexistent at 100 μm. Material was seen both in front of and behind the comet's orbital position (at least 2° ahead and 9° behind in mean anomaly). In addition to being more extended, the lagging material was substantially brighter than the material ahead of the comet's position. This is probably due largely to the emission of smaller particles more sensitive to radiation pressure, as Eaton *et al.* discussed for the "anomalous" tail of Tempel 2 (*7*).

Comet Gunn has one of the larger perihelion distances of the known periodic comets (2.46 AU). Debris in the orbit of this comet is no surprise, however, because the comet is active over most of its orbit and recently exhibited a tail at visible wavelengths near aphelion (*9*). Such activity has been noted by E. Roemer (*10*). The IRAS data also showed a dust coma ~9 arc minutes in diameter, corresponding to ~1,000,000 km at the comet.

So far, the close association of dust trails with comet positions suggests that the trails are replenished with material as the comet passes perihelion, where the mass loss rate of the nucleus is greatest. The trail fades as its constituent debris spreads out along the orbit, and the comet's activity, which acts as a source of trail material, diminishes as the comet heads for aphelion. This situation is temporary, however, as the comet begins moving in toward the sun again and material is fed into the dust trail as the comet nucleus starts heating up and giving off ice and debris.

Calculations of the time it would take for material to move ahead of the orbital positions of comets Tempel 2 and Gunn, at a relative velocity on the order of meters per second, suggest an age for the dust trails of hundreds of years. Thus, we are seeing the product of numerous emission events, superimposed on each other over many tens of orbits.

The one trail exhibiting any divergent behavior is in the orbit of comet Encke. The Encke dust trail was observed heading in toward the sun at heliocentric distances ranging from 4 AU, near aphelion, to 3.5 AU. It extended from less than 16° to more than 80° behind the comet's orbital position in mean anomaly, making it easily the longest trail we have yet observed (over 2 AU long). It was seen only at 60 μm and (very faintly) at 25 μm. This is consistent with the effects of its having a colder blackbody temperature; particles in the Tempel 2 dust trail are closer to the sun by more than 2 AU.

Encke's material appears to have a greater apparent thickness perpendicular to the line of sight than any other trail by nearly a factor of 2. The viewing angle is ~3°, so we are seeing a greater cross section of material perpendicular to the orbital plane of the comet than in many of the observations of the Tempel 2 trail. Radiation forces, acting over time to disperse the material after ejection, will spread material along the orbit and in the orbital plane, but this action does not account for the greater dispersion of material normal to the orbital plane. Since Encke approaches closer to the sun than any other known periodic comet (0.34 AU), the greater width of the trail might be due to greater velocities of debris ejection during perihelion passage.

Furthermore, no dust has been found ahead of the comet, and the trail behind it appears to be detached, fading as it nears the comet's orbital position. The apparent detachment of the trail indicates, in this case, episodic cometary activity related to dust trail formation. The absence of a trail ahead of the comet suggests that the particles emitted are almost entirely in a size range sensitive to radiation pressure, as has been suggested for most of the comet Gunn trail material and some of the Tempel 2 trail material. Comet Encke might be fundamentally different from comets Tempel 2 or Gunn and may possess a refractory component of its nucleus that differs in composition, density, or particle-size distribution. Analysis of these and other dust trails may provide another means of distinguishing groups of comets.

Meteor streams are thought to have originated by the same processes that produce dust trails. Many meteor streams are associated with specific comets, and three such streams are associated with comet Encke: the Daytime Taurids, North Taurids, and South Taurids (*11*). None of these, however, correspond to the Encke dust trail. As yet, none of the trails we have examined can be linked to any known meteor stream, which are possibly too diffuse to have been observed by IRAS. Dust trails, however, provide the genetic link between meteor streams and comet nuclei. Extended along a comet's orbit, dust trail segments will experience orbital perturbations different from those of the parent comet. Eventually, this might lead to the perturbation of the dust trail material into an orbit that diverges substantially from that of the parent comet, resulting in a decoupled meteor stream.

Examination of the IRAS data indicates that there may be more than 100 dust trails near the limit of detection. Almost all of the trails are much shorter than those described here, with an apparent length of only a few degrees. Their association with periodic comets is implied by their apparent inclinations of less than 40° with respect to the plane of the ecliptic and the above identifications of comet sources. Marsden (*12*) lists 136 comets as periodic. If the dust trails are associated predominantly with this group of objects, their number suggests that we may be seeing a number of dust trails that derive from comets not yet discovered. We have determined that five trails (in the same field as Fig. 1 and elsewhere) are not associated with any known periodic comet. We have also tentatively identified additional trails in the orbits of comets Tempel 1, Kopff, and Shoemaker 2.

Among other possible sources of dust trails are asteroids, which also have generally low inclinations. Since the initial result of an asteroid collision is the distribution of debris along its orbit (*13*), some of the dust trails could be asteroidal in origin.

It is conceivable that in a future comet rendezvous mission a spacecraft might be able to directly sample and analyze the rocky component of a comet nucleus by approaching the comet along its orbit and sampling its associated dust trail. The relative velocity of such a spacecraft and the trail debris would be quite low (meters per second). Following a comet through perihelion, the spacecraft could monitor trail development and the corresponding processes at the nucleus. Such a mission could determine particle-size distributions, structures, and compositions of this material, which would increase our understanding of cometary origins and the formation of our solar system.

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14. We thank E. Roemer for reviewing this manuscript and providing many useful comments and suggestions. We also thank S. Larson for helpful suggestions and discussions. Software provided by D. Tholen aided in the identification of the Gunn dust trail. We thank J. Spencer for useful suggestions in image processing and P. Maloney for identifying planetary nebula NGC 7293. Supported by NSF grant AST-8206173 and NASA grant NSG-7114.

9 December 1985; accepted 18 March 1986