VII

ORIGIN OF INTERPLANETARY DUST
FROM COMETS AND ASTEROIDS, BACK TO INTERSTELLAR DUST

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COMETARY AND ASTEROIDAL SOURCES OF INTERPLANETARY DUST

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ABSTRACT. The Infrared Astronomical Satellite has provided extensive observations of the zodiacal cloud at high spatial resolution which will not be matched in the forseeable future. Within the zodiacal cloud, IRAS discovered extended dust structures providing the link between the interplanetary dust complex and the asteroids and comets which are its source. These are the asteroid dust bands and the cometary dust trails.

1. Introduction

The origin of the zodiacal cloud has long been thought to be primarily cometary [1,2,3]. Estimates of dust production by short-period comets at the current epoch, however, have fallen far short of that needed to maintain the cloud against losses by radiation forces (after collisional evolution) [4,5]. A cometary cloud would be replenished by the occasional capture of "new", highly active comets into short-period orbits. Whipple [2] has suggested P/Encke as having been such a source in the past.

Asteroid collisions also have been considered to be a source of interplanetary dust, but the lack of observational constraints on the population of boulder-sized precursors to dust, and uncertainties in the mechanics of collisional disruption of these and larger bodies, have made it difficult to estimate the asteroidal contribution. When the Pioneer spacecraft failed to detect an enhancement in the spatial density of interplanetary dust as they passed through the asteroid belt, the contribution of asteroid collisions to the zodiacal complex consequently was thought to be small compared to comets [6].

Our knowledge of the relationship between comets, asteroids, and interplanetary dust is now undergoing significant revision as a result of extensive observations made by the Infrared Astronomical Satellite (IRAS). The mission of this small orbiting telescope was to conduct the first sensitive survey of the entire sky at thermal

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Figure 1. The sky at 25 μm as seen by IRAS. The field is 28° in width and is centered near 1^h RA and 0° DEC (1950). East is to the left and North is up. The bright band diagonally transecting the image is the central dust band complex, associated with dust generated in the Koronis and Themis asteroid families. The long narrow trail beneath the central dust band is the Tempel 2 dust trail. P/Tempel 2 is detected near the eastern edge of the field. The background cloudlike structures are the infrared cirrus.

wavelengths [7]. In the course of this successful survey IRAS detected previously unknown, extended dust structures: the missing links between the zodiacal cloud and its cometary and asteroidal sources. These were the cometary debris trails [8] and the asteroid dust bands [9] (Fig. 1).

2. A Cometary Source

Cometary dust or debris trails are long, narrow emission features which in the IRAS data appear very much like the airplane contrails from which their name is derived. They are associated with some short-period comets, generally extending over a small fraction of their orbits [8]. Millimeter and larger in size, trail particles are ejected from their parent comets at very low velocities ($\sim$ 1 m/s), and are relatively insensitive to radiation pressure, compared to comet *tail* particles. This is why they are seen very near the projected orbits of their parent comets. Trails are not rings. They do not extend completely around comet orbits. The timescale for such dispersion is large compared to the mean times between shifts in short-period

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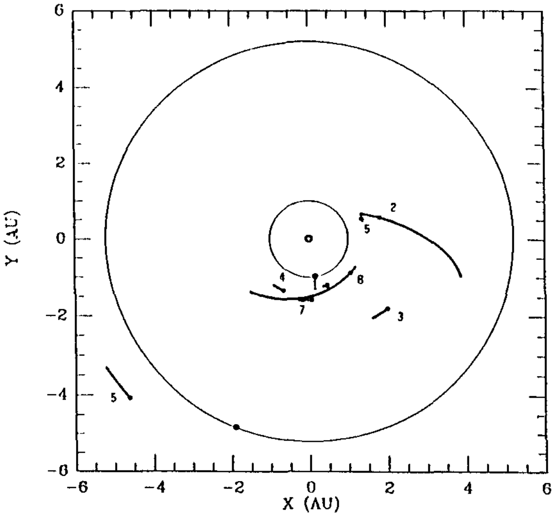

Figure 2. The eight trails associated with known short-period comets are projected onto the ecliptic plane. Positions were calculated for July 1, 1983. They are (1) Churyomov-Gerasimenko, (2) Encke, (3) Gunn, (4) Kopff, (5) Pons-Winnecke, (6) Schwassmann-Wachmann 1, (7) Tempel 1, and (8) Tempel 2. The orbits and positions of Earth and Jupiter are shown for scale.

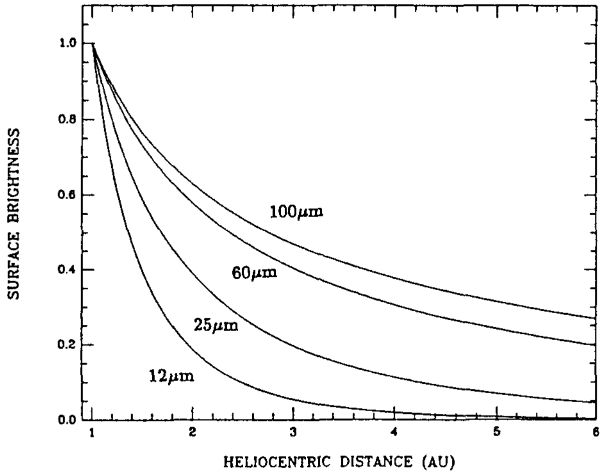

Figure 3. The surface brightness of a blackbody integrated over the IRAS passbands is shown as a function of heliocentric distance. Values are ratioed to 1 AU.

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comet orbits due to gravitational perturbations by Jupiter [10].

A survey of all dust trails observed by IRAS has been completed [11]. A total of 8 trails were found in association with known short-period comets (Fig. 2). Nine fainter trails ("orphans") were also detected not associated with any known source, and it is presumed that they represent the first detections of 9 short-period comets. This is bolstered by the detection of cometary comas connected to two of the orphan trails. With the exception of Encke and Schwassmann-Wachmann 1, which are known to be anomalously active, trails tend to be observed near perihelion, and are associated with comets having the lowest perihelion distances. Trails were observed in orbital locations where they were hottest, and hence brightest at thermal wavelengths. Since short-period comets tend to have aphelion near Jupiter's orbit, and particles in elliptical orbits spend much more time near aphelion than perihelion, trail particles associated with other comets would tend to be much colder, hence fainter, in the IRAS passbands (Fig. 3). It is inferred that all short-period comets have trails, and that when the Infrared Space Observatory (ISO) is launched in 1993, it will see (with a few exceptions) a different ensemble of comet trails [11].

The generality of the dust trail phenomenon is important when considering the rate at which short-period comets supply mass to the interplanetary dust complex. A comparison with total mass-loss rates estimated from groundbased observations [17] indicates that at least 10 times more mass is lost in refractory trail particles [11]. Thus, comets are losing the great bulk of their mass in large particles, and at rates which may allow for the "steady-state" replenishment of the cloud. If the relative mass loss rates of refractory and volatile material inferred from trail studies represent the cosmogonic mass ratio, then our understanding the location and conditions of comet formation would have to be radically revised. However, it is more likely that short-period comets, having undergone significant thermal evolution, accumulate an increasingly refractory layer (mantle) over the nucleus surface as the available volatiles become depleted. An understanding of the physical properties of trail particles may then be extrapolated directly to the mantle.

Analysis of the thermal spectrum of the trail particles [11] indicates that they are very dark and porous or low-density. This is consistent with the Giotto and Vega observations of the Halley comet nucleus [12,13], and suggests that other short-period nuclei may be similar. Groundbased observations of comet nuclei have also suggested low-albedo surfaces [14,15,16].

In its observations of the zodiacal cloud, IRAS was most sensitive to particle radii of several microns at 12 and 25 μm [18]. Since trail particles are much larger, the cometary component of this cloud would arise from the collisional comminution of trail particles over time. However, IRAS also observed the cloud to have a high degree of azimuthal symmetry about the sun (to within a few percent of predicted surface brightness at 12 and 25 μm) [19]. As trail particles are comminuted into smaller sizes, they would be increasingly sensitive to radiation pressure and at some point might find themselves in Jupiter-crossing orbits. Numerical simulations of the dynamical evolution of such particles directly ejected from P/Encke, suggests that their orbital nodes would be distributed over all longitudes as a consequence

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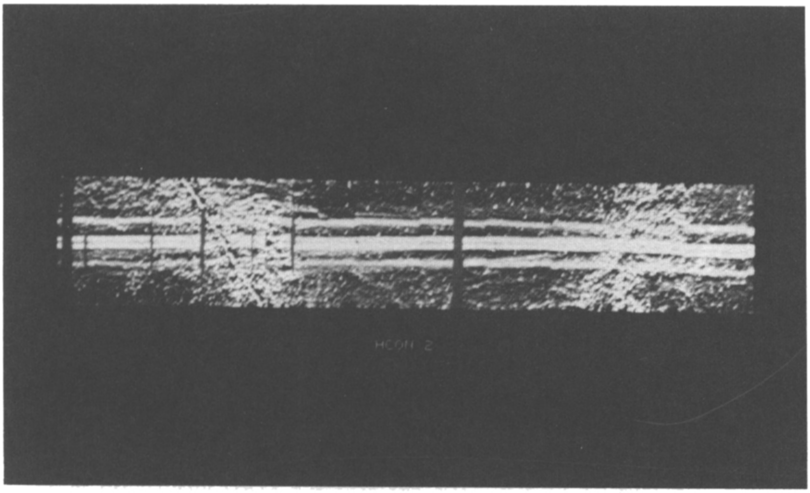

Figure 4. The ecliptic plane in cylindrical projection. IRAS scans have been high-pass filtered in ecliptic latitude to enhance the zodiacal dust band structures. Longitude increases to the left, beginning at 0°. Latitudes span ±30°. The principal bands are near 0° and ±9° latitude. Breaks and shifts in band positions are parallactic.

of gravitational interactions with Jupiter [20]. This could result in the cometary component of the zodiacal cloud having reasonable azimuthal symmetry about the sun. Otherwise, a cometary cloud would be very "bumpy".

3. Dust From The Asteroid Belt

Another source of interplanetary dust is asteroid collisions. One of the most significant discoveries made by IRAS was of regions of contemporary collisional dust production in the asteroid belt, evidenced by the zodiacal dust bands [9] (Fig. 4). The dust bands are tori of dust surrounding the inner solar system, formed when particles having similar orbital elements (a,e,i) have nodes distributed over all longitudes in the plane of symmetry of the torus. Orbit volume densities are maximum near the edges of the tori, and enhanced in the "corners" (Fig. 5) [21]. This gives rise to the appearance of parallel bands when viewed from the Earth.

The similarity in latitudes of the dust bands to the inclinations of the principal Hirayama asteroid families, in the outer main belt, led to the suggestion that the two were associated [22]. The outer pair were thought to arise from the Eos family, while the inner pair was associated primarily with the Themis family. Further analysis of the central band pair further resolved them into two components associated with

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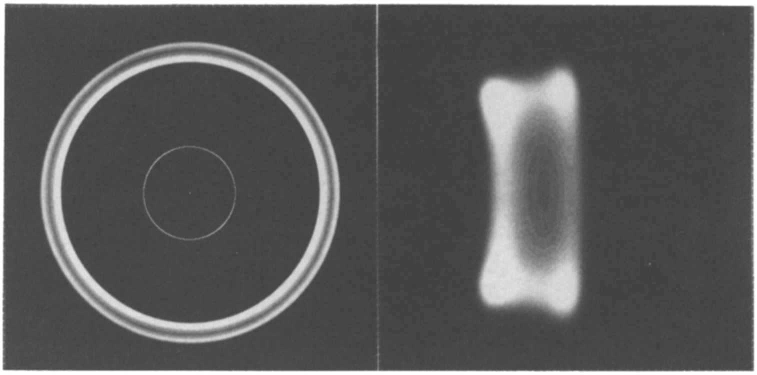

Figure 5. Model dust tori associated with the Eos asteroid family. On the left is a cut through the ecliptic plane, with the Earth's orbit shown for scale. On the right is the radial cross-section of the torus (the Sun is to the left). The mean orbital elements are the same as the known family members, and 2σ dispersions are assumed. The radial torus width is ~ 0.6 AU.

the Themis and Koronis families, respectively [21,23]. Several fainter bands also have been detected [23].

These asteroid families are the sites of the ancient catastrophic disruption of large asteroids. We are not seeing dust from that collisional event, however - such dust would have been lost long ago by Poynting-Robertson drag. Instead, we are witnessing the ongoing production of dust as the collisional fragments are themselves being broken up further into smaller and smaller sizes over time. Mass is being redistributed continually through collisions to smaller size debris until it is small enough to be removed from the families by radiation forces [24]. Calculations by Reach (this volume) indicate that material generated in the bands may be sufficient to supply the zodiacal cloud as it evolves towards the sun under Poynting-Robertson drag. In this case, the entire cloud observed by IRAS could be viewed as an extension of the major outer main belt asteroid families. This would satisfy the criterion of an immediate zodiacal cloud source that is distributed smoothly already in longitude. That asteroid dust production may be dominant in the outer main belt is also supported by the absence of significant dust bands associated with inner belt families [21].

Isolating the sources of dust production in the asteroid belt to a few specific and well-defined regions has consequences which may be testable at the Earth's orbit. Taking into consideration the dynamical evolution of torus particle orbits

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as they decay towards the Sun, dust collection experiments should evidence annual modulations of interplanetary dust components [25]. By determining the amplitude and node of these variations for a given particle size, the specific source region (e.g. asteroid family) may be identified. Thus, interplanetary dust studies may allow the minerologies associated with specific asteroid taxa to be determined [25].

5. Future Opportunities

Valuable new information in the study of specific sources of interplanetary dust will be gained with the upcoming Infrared Space Observatory (ISO) and the planned Space Infrared Telescope Facility (SIRTF). Archival analysis of data from the Cosmic Background Explorer (COBE) will add to our understanding of the relationship between the dust bands and the zodiacal complex, but is not expected to provide new detections of cometary dust trails (e.g. Tempel 2), because of its large field of view (and assuming pre-launch detector sensitivity requirements).

Since many of these sources were discovered after IRAS ceased functioning, ISO and SIRTF will offer the first opportunities to design specific observations of these phenomena to answer questions such as the existence of trails associated with other short-period comets and the nature and origin of the fainter dust bands and mysterious Type II dust trails [23]. Greater wavelength coverage and sensitivities will allow for a better understanding of the physical properties of dust as it is generated by comets and asteroids, as well as the underlying processes governing their release. By the next Colloquium on the origin and evolution of interplanetary dust, the global question contained in the title will have been answered in some detail.

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