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ORIGIN OF THE INTERPLANETARY DUST CLOUD

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Sources of Interplanetary Dust

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Abstract. Asteroids, comets and interstellar dust are possible sources of the particles that constitute the dust in the inner solar system. Each of these components gives rise to particular, characteristic features, the amplitudes of which can be used to estimate the size of the associated source. The asteroidal component feeds the dust bands and the Earth's resonant ring, while the cometary component may account for the large scale height of the zodiacal cloud observed at 1 *AU* Previous discussions of the observed strengths of these various features indicated that the source of about one third of the thermal flux observed, for example, in the IRAS 25μm waveband is asteroidal, while two thirds is cometary. However, a variety of assumptions go into this calculation (the size-frequency distribution of the particles is particularly significant) and we now know that the result is highly dependent on these assumptions. The zodiacal cloud is also the source of the IDPs collected on Earth. Because of strong gravitational focusing by the Earth of particles in low e and I orbits, it is probable that the majority of IDPs originate from asteroids, particularly those asteroids in the Themis and Koronis families.

1. Introduction

The particles in the zodiacal cloud are observed by a variety of means that include: (1) radar observations of meteor streams (Southworth and Sekanina, 1973); (2) optical and infrared observations (Levasseur-Regourd & Dumont, 1980; Leinert and Grün, 1990); (3) in situ detectors on spacecraft (Grün and Staubach, 1996); and (4) through the collection of particles (IDPs) that impact our atmosphere (Brownlee, 1978). A good review of this subject has been given by Leinert and Grün (1990). Each mode of detection is biased towards a different particle size and possibly towards particles of different origins. An attempt has been made by Divine (1993) to construct a model that encompasses the whole particle population and this model was discussed at this meeting by Grün and Staubach (1996). Our approach is less ambitious in that it concentrates on particles in a narrow diameter range (1 to 100μm) and is concerned mostly with the IRAS and COBE infrared observations. On the other hand, it may be more ambitious because it purports to follow the evolution of particles from source to sink and allows for a wide range of dynamical phenomena (Dermott *et al.*, 1992, 1994a). One of the recent successes of this approach was the interpretation of the observed trailing/leading asymmetry of the zodiacal cloud (Dermott *et al.*, 1988) in terms of the Earth's resonant ring (Dermott *et al.*, 1994b, 1996a; Jayaraman and Dermott, 1996a,b,c).

In this short overview of our recent work we discuss the application of this "source to sink" approach to the dust bands, the broad-scale background zodiacal cloud, and the Earth's resonant ring. We also discuss some of the recent COBE observations.

2. Asteroidal Dust Bands

We have demonstrated that the particles in a dust band must have a common proper inclination, although the particles may have some small dispersion about that inclination. This fact alone argues that the bands are asteroidal. It is impossible for particles with large orbital eccentricities (≥ 0.2) to maintain a common proper inclination and this rules out a cometary source (Liou *et al.*, 1995a). The observed forced inclinations and forced nodes of the bands also place their source unambiguously in the asteroid belt (Dermott *et al.*, 1992, 1994a). The central dust bands appear to be associated with the Themis and Koronis asteroid families but the association of the "ten-degree" bands with the Eos family has proved to be problematical because the proper inclination of the Eos family appears to be too large (Dermott *et al.*, 1994a).

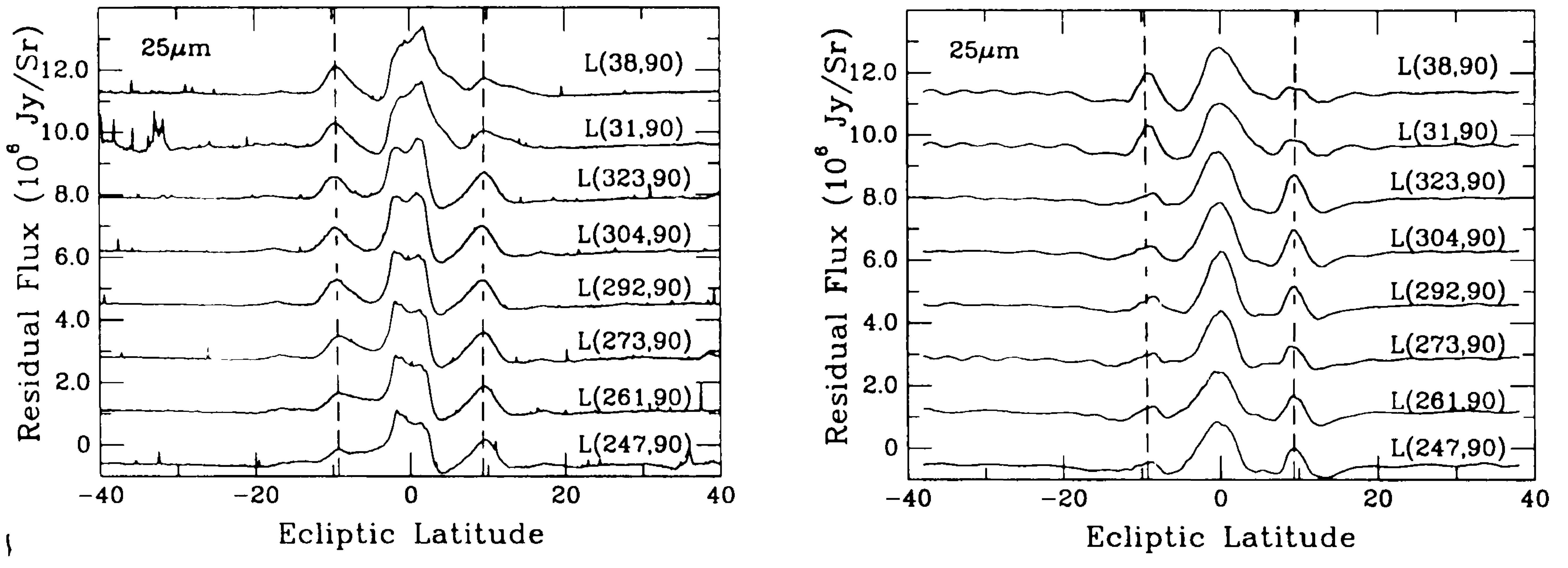

Figure 1. (a) Observed structure of the dust bands obtained by filtering out the broadscale background. The label L(38,90) indicates that the scan was obtained in the leading (L) direction with an elongation angle of 90° while the ecliptic longitude of the Earth was 38° (b) The fluxes from our model dust bands shown here were obtained using the same filter that was used to obtain the observations shown in (a).

Some IRAS observations of the dust bands are shown in Fig. 1(a). The observed amplitudes of these bands are highly dependent on the characteristics of the filter that is used to separate the bands from the broad-scale background. Thus, any direct use of the amplitudes of the filtered bands to derive, for example, a color temperature, is not meaningful. Most ($\sim 90\%$) of the flux from a model dust band (see Fig. 2) merges with and is indistinguishable from the broad-scale background. Only if the model dust bands are added to an appropriate broad-scale background and the resultant signal filtered using the same filter that was used to obtain the observations can we make a valid comparison between observation and theory (Dermott *et al.*, 1994a). An example of such a comparison is shown in Fig. 1.

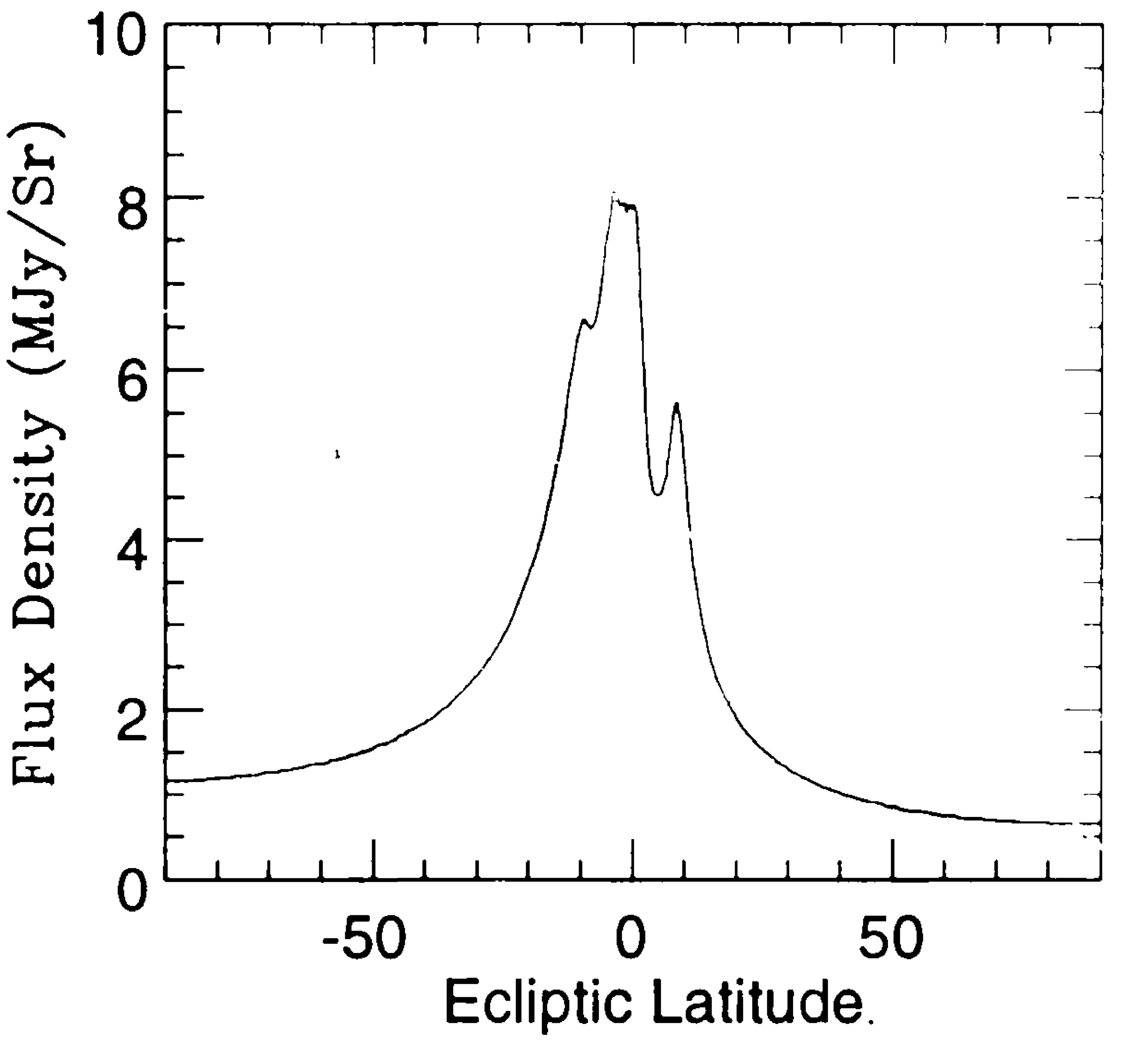

Figure 2. The flux from the unfiltered model dust band used to obtain the results shown in Figure 1(b).

Note, in particular, the marked variation of the amplitudes of the North and South ten-degree bands with the longitude of the Earth. Although the amplitudes of the bands shown in Fig. 1(a) constitute $\sim$ 1% of the total signal, the flux from the model dust band shown in Fig. 2 constitutes $\sim$ 10% of the total signal. Thus, in a limited sense, the dust bands alone constitute $\sim$ 10% of the zodiacal cloud. (We use the term "limited sense" because it would be more meaningful to make the more precise statement that "the source of about $\sim$ 10% of the thermal flux observed in the IRAS 25μm waveband is asteroidal and associated with the dust bands"). From the observed ratio of family to non-family asteroids we estimate that perhaps about one-third of the zodiacal cloud is asteroidal (Dermott *et al.*, 1994a; Durda and Dermott, 1996), but this calculation assumes that the dust populations in the families and the non-families are equilibrium distributions and that they have the same size-frequency distribution index. We are now aware that this index depends on the strength of the particles and thus that there may be significant differences between the various asteroidal sources (Durda and Dermott, 1996).

3. Asymmetries of the Zodiacal Cloud

The Earth's resonant circumsolar ring originates from asteroidal particles that spiral in towards the Sun due to Poynting-Robertson light drag and get captured in outer mean motion resonances with the Earth (Schmidt, 1967; Jackson & Zook, 1989; Dermott *et al.*, 1994b). We are reasonably confident that the particles in the ring are asteroidal and not cometary because only particles with low orbital eccentricities have significant probabilities of capture into outer mean motion resonance. It is possible for cometary particles to be captured into interior mean motion resonances with Jupiter and then have their orbital eccentricities reduced to asteroidal values (Liou & Zook, 1996), but it has not been shown that this mechanism provides a significant source of particles in near-circular orbits.

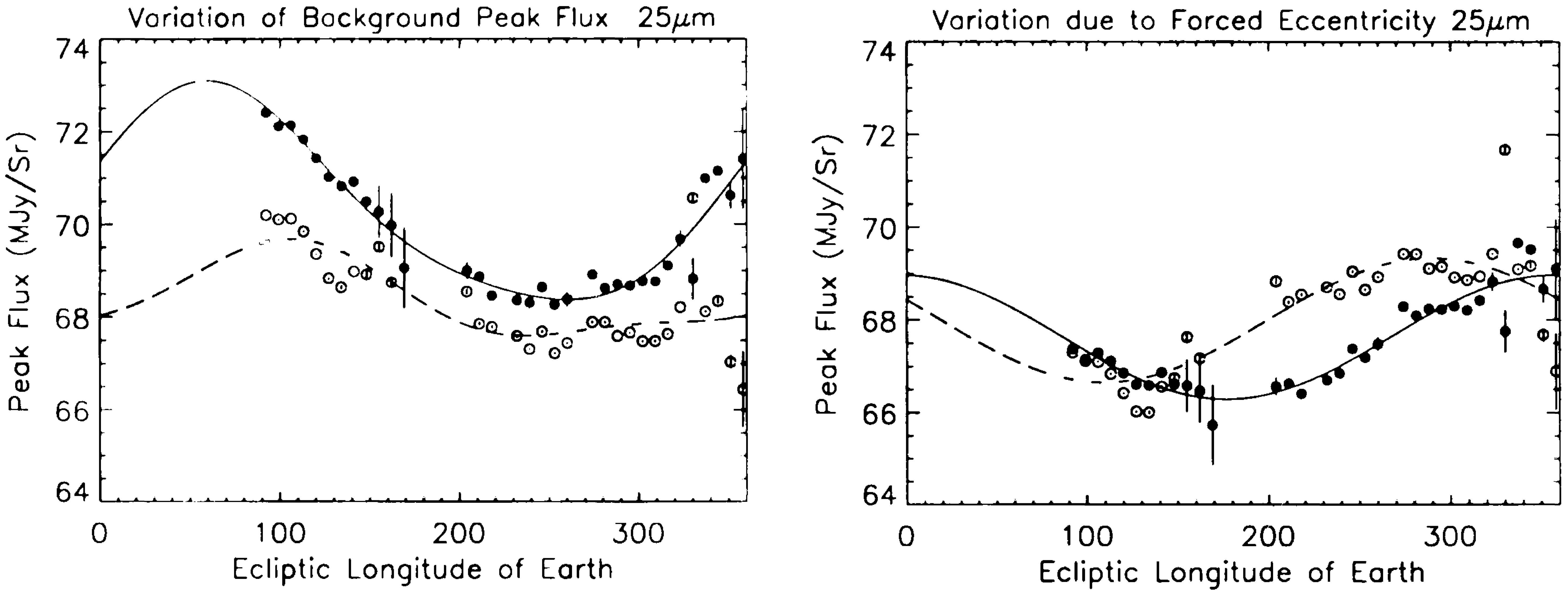

Figure 3. (a) COBE observations of the variation of the peak background flux with the ecliptic longitude of the Earth obtained at a constant elongation angle of 90° in the trailing (upper solid curve and filled circles) and leading (lower dashed curve and open circles) directions. (b) COBE observations of the variation of the peak background flux with the ecliptic longitude of the Earth due solely to the offset of the Sun from the center of symmetry of the cloud (Dermott *et al.*, 1996).

We have shown that asteroidal particles are captured into a large range of resonant orbits that form a pattern that is near stationary in a frame centered on the Sun and corotating with the Earth's mean motion. The particles trapped in the resonances form a toroidal circumsolar ring that contains the Earth embedded in a cavity and a cloud or concentration of particles that trails the Earth in its orbit. The chief observational consequence of this trailing cloud is the observed trailing/leading asymmetry of the zodiacal cloud. At all times of the year, infrared observations of the zodiacal cloud in the trailing direction (opposite to the Earth's orbital motion) tend to be significantly greater than those in the leading direction. The IRAS data showed evidence of an asymmetry $\sim$ 3-4% in the 12, 25 and 60μm wavebands (Dermott *et al.*, 1988, 1994). Recently, the DIRBE data have provided much more accurate and extensive measurements of the infrared flux in 10 wavebands from 1.2 to 240μm and some of these wavebands show very clear trailing/leading asymmetries (Dermott *et al.*, 1996; Jayaraman and Dermott, 1996a,b,c). Some of the COBE data is shown in Fig. 3. Reach et al. (1995) subtracted empirical models of the background zodiacal cloud and the dust bands from the COBE data to obtain an image of the residual flux that is a striking match to the structure of the trailing dust cloud that appeared on the cover of *Nature* on June 30, 1994 (Dermott *et al.*, 1994b; Jayaraman and Dermott, 1996a,b,c). A new all-sky map of the model ring, as seen from the Earth, is shown in Fig. 4.

Analysis of the structure of the ring enables us to determine the fraction of asteroidal particles in the zodiacal cloud (or, more accurately, the fraction of particles at 1 AU with low orbital eccentricities). The number of particles in the ring and the leading/trailing asymmetry are directly dependent upon the number of asteroidal particles reaching the inner solar system, which in turn is dictated by the asteroidal dust production rate. We have calculated capture probabilities for asteroidal particles of density 2.5 g/cm^3 ranging in diameter from 9 to 45μm and found that the total capture probability decreases steeply with decreasing size providing a lower cut-off for particle size in the ring of about 5μm. There is also an effective cut-off at larger sizes despite the higher trapping probability because although the larger particles have lower drag rates and are easily captured into resonance, their resonant orbits are near-symmetric with respect to the Sun-Earth line and they do not contribute to the trailing/leading asymmetry of the cloud. Thus, the observed asymmetry is caused by particle sizes in the diameter range 5-30μm. We assume here that the particles have a density of 2.5 g/cm^3 and are spherical. If the density is, for example, only 1 g/cm^3, then the sizes would be a factor of 2.5 larger.

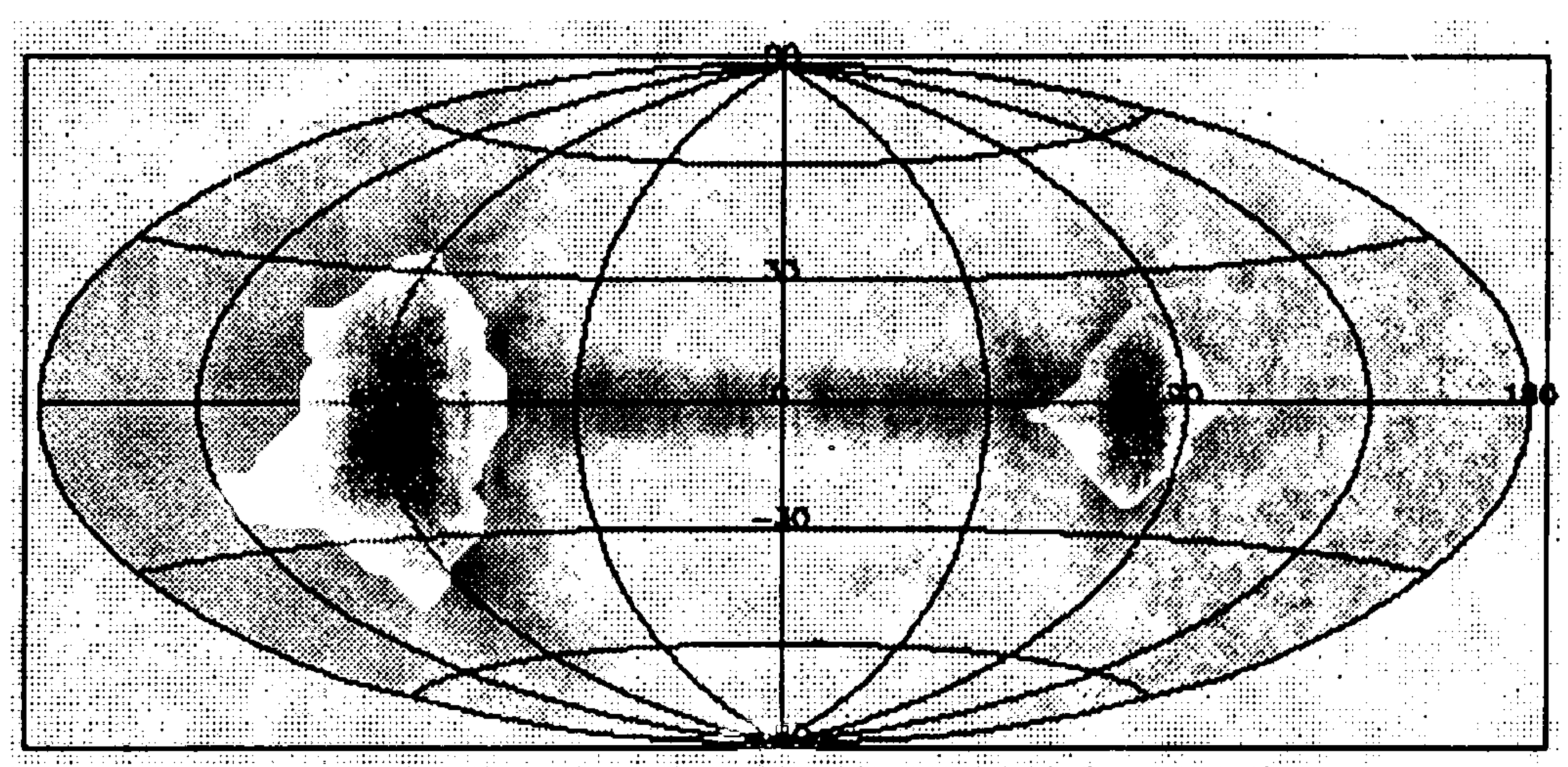

Figure 4. Predicted flux from a model resonant ring of 12μm diameter asteroidal silicate particles as viewed from the Earth. Geocentric longitude is measured anticlockwise from the line joining the Sun and Earth as viewed from the North. The trailing dust cloud covers 35° in longitude and is centered close to 90° on the left-hand side of the figure (Jayaraman & Dermott, 1996a,b,c).

We have constructed single-size particle rings for 9, 12, 15, 19, 25 and 36μm diameter, astronomical silicate (Draine & Lee, 1984), particles and have combined these according to a power law size-frequency distribution, allowing for the variation of capture probability with size. Predictions derived from the resultant model ring have been compared with observations of the ring in the various COBE (DIRBE) wavebands (Jayaraman and Dermott, 1996b). The resonant ring and the dust bands may be our best hope for understanding the nature of the particles in the zodiacal cloud and disentangling the many factors that have a bearing on the observations. The ring is special in that: (1) we probably know the origin of the particles and thus we know that we are dealing with a single class of particles (this also applies to the dust bands); (2) the particles in the ring that contribute to the trailing/leading asymmetry have a narrow range of sizes; and (3) the location or distribution of the particles in space is known. However, many unknown factors are essential parts of any ring model. These factors include: (1) the density of the particles (these determine the drag rates and the capture probabilities); (2) their scattering properties; (3)

the index of the power law that we assume describes the particle size-frequency distribution and the variation of this index with distance from the Sun.

The results are very sensitive to the size-frequency distribution index, q, defined by the equation

$$N(d) = \frac{1}{3(q-1)} \left(\frac{d_o}{d}\right)^{3(q-1)} \tag{1}$$

where $N(d)$ is the number of particles with diameter $> d$ and d_o is a constant. In our most recent work on the ring (Jayaraman and Dermott, 1996b), we have assumed that the particles have optical properties corresponding to astronomical silicate and we have used the observed magnitudes of the trailing/leading asymmetries to determine the fraction of particles in the zodiacal cloud at 1 *AU* that are asteroidal. We find that this fraction varies from 10% to 100% as q varies from 1.70 to 1.95. Thus, if we had independent evidence that $q = 1.95$, then we could conclude that the particles in the zodiacal cloud with diameters in the range 5-30μm are mostly asteroidal. Unfortunately, the value of q for asteroidal particles alone (this may not be the same as the mean value of q for the cloud as a whole) is not known.

Other asymmetries of the zodiacal cloud arise from: (1) The inclination of the cloud with respect to the ecliptic. A promising start has been made on accounting for the observed plane of symmetry of the cloud in terms of the dynamics of asteroidal particles (Dermott *et al.*, 1992). The inclination of the cloud with respect to the ecliptic gives rise to a double sinusoidal variation with the longitude of the Earth of the peak brightness of the cloud as observed at a constant elongation angle of 90° in either the trailing or the leading directions. (2) Variations in the latter brightness also arise from the Earth's eccentricity, and from (3) the displacement of the Sun from the center of symmetry of the cloud due to the common forced eccentricities of the dust particle orbits. All three of these asymmetries have been observed in the COBE data and the observational information is sufficient to allow a clear separation of the individual asymmetries. The asymmetry due solely to displacement of the Sun from the center of symmetry of the cloud is shown in Fig. 3. Both the direction and the magnitude of the displacement is in good agreement with predictions based on the dynamics of asteroidal particles (Dermott *et al.*, 1996).

From the above arguments it would appear that there is a strong case for believing that the particles in the zodiacal cloud in the 1 to 100μm diameter size range are largely asteroidal. This could be the case. However, we have now shown that this would require the asteroidal q to be as high as 1.95. Two further problems for a purely asteroidal model of the zodiacal cloud arise when we consider the observed variations in flux at the North and South ecliptic poles. The COBE observations in the 25μm waveband are shown in Fig. 5(a). The predicted flux from a purely asteroidal model is shown in Fig. 5(b). The flux in this model was normalized by demanding that the peak, near-ecliptic, flux observed with an elongation angle of 90° matches the COBE observations. The first problem with the purely asteroidal model is that the model polar flux is a factor of two less than the observed polar flux. The second problem is that the ratio of the maximum difference in the North and South fluxes to the mean flux is higher in the model than in the COBE data. A possible solution to the

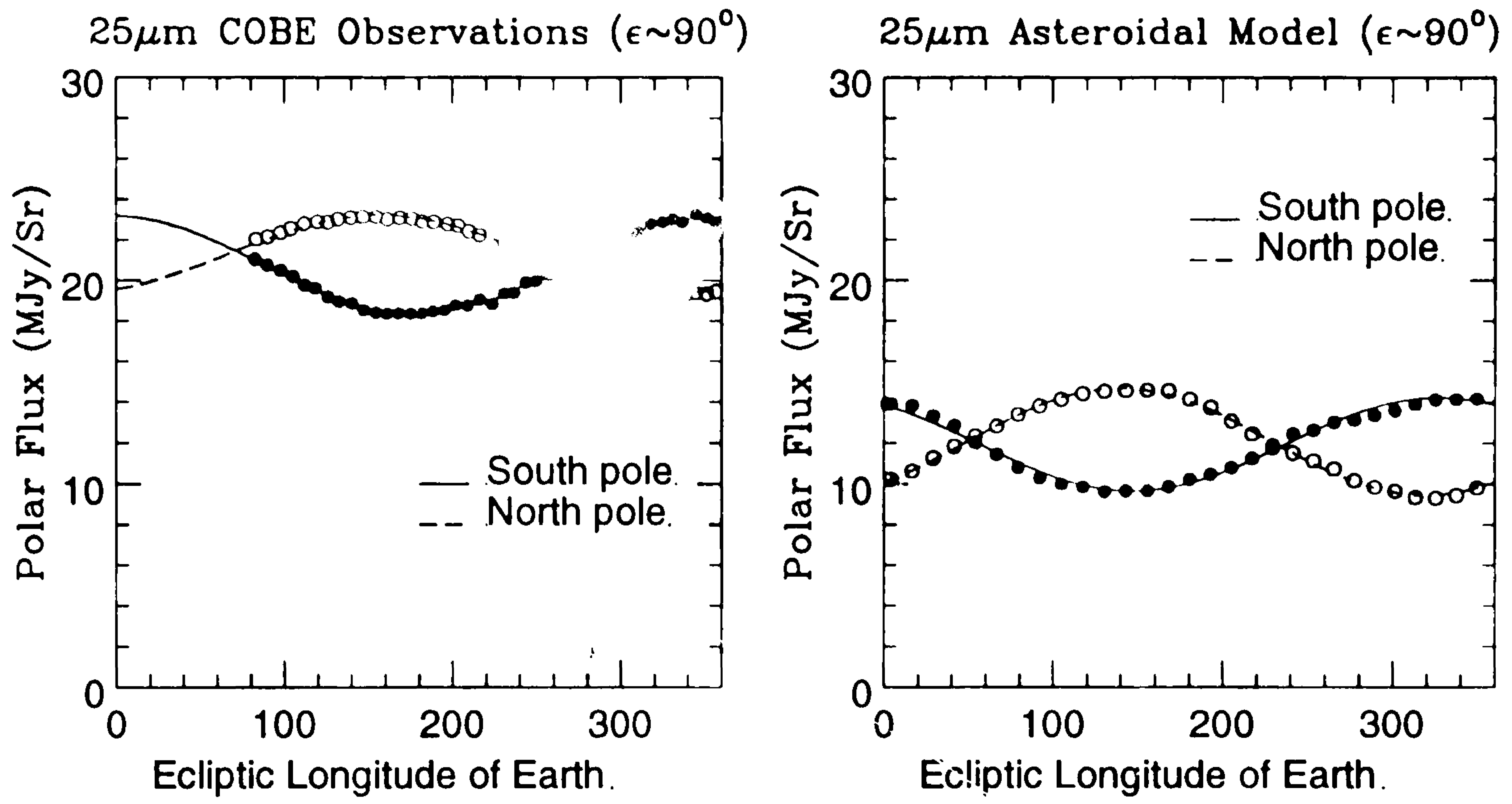

Figure 5. (a) COBE observations of the polar flux (b) Polar flux predicted by an asteroidal model of the background zodiacal cloud based on single size particles of astronomical silicate of diameter 12μm. The model flux has been normalized to match the peak ecliptic flux observed in the leading direction with an elongation angle of 90°.

first problem is to allow the effective area of the dust particles to increase as the particles migrate towards the Sun (the model calculations do not allow for any particle breakup and thus the effective area of the particles remains constant). However, this would not solve the second problem because the ratio of the model polar fluxes would remain unchanged. The ratio of the model polar fluxes could be reduced by decreasing the mean forced inclinations of the particles at 1 *AU*. The forced inclination determines the inclination of the plane of symmetry of the cloud with respect to the ecliptic and hence the North/South asymmetry of the cloud. It is possible that the forced inclinations are small but this would require the particles to have high orbital decay rates and thus to be very small. This problem requires further investigation. A second way to solve this "scale height" problem is to allow that the cloud has a cometary component and that this component, unlike the asteroidal component, has a large vertical scale height at 1 *AU*.

4. Origin of IDPs

At this point in time, we have to admit that the fraction of particles in the zodiacal cloud that is asteroidal rather than cometary has not been determined. Although, by further analyzing the structure of the cloud, as observed in the large range of wavebands that IRAS and COBE have now made available to us, in terms of the dynamics of the particles, we can expect to make substantially more progress than has been made to date. However, there are two features of the zodiacal cloud whose origins appear to be quite unambiguous and these are the two near-ecliptic dust bands associated with the Themis and Koronis asteroid families. These components of the cloud are certainly minor — the particles associated with this source probably constitute no more than 3-5% of the cloud as a whole (Dermott *et al.*, 1994a). However, these two families may be the source of a large fraction, even a dominant fraction, of the interplanetary dust particles collected in the Earth's atmosphere.

The gravitational capture cross-section of the Earth is determined by the relative velocities of the particles with respect to the Earth and these are determined by the orbital eccentricities and inclinations (with respect to the ecliptic) of the particles at 1 *AU*. Poynting-Robertson light drag reduces the eccentricities of both asteroidal and cometary particles, but because of their lower initial eccentricities, the relative velocities of typical asteroidal particles at 1 *AU* are much lower than those of typical cometary particles at 1 *AU*. Flynn (1990) pointed out that this disparity in relative velocities biases the atmospheric IDP collections in favor of low relative velocity asteroidal particles. We calculate that typical asteroidal particles are $\sim$ 16 times more likely to be captured by the Earth than a typical cometary particle. However, not all asteroidal particles are typical. We certainly know that particles from the Themis and Koronis families, that constitute the observed near-ecliptic dust bands, are atypical in that they have very low inclinations with respect to the ecliptic. Because of their low inclinations, we calculate that these particles have capture cross-sections $\sim$ 200 times greater than a typical cometary particle. Given these capture cross-sections, we have shown that even if the fraction of particles in the zodiacal cloud originating from Themis and Koronis is as low as 2%, then, if the fraction of particles in the zodiacal cloud originating from comets is even as high as, for example, 80%, the fraction of IDPs collected in the Earth's atmosphere originating from Themis and Koronis will be greater than 50%, while the fraction originating from comets will be no more than $\sim$ 10% (Kortenkamp *et al.*, 1996; Dermott & Kortenkamp, 1996). Analysis of existing IDP collections shows that even the most diverse particles may originate from just one or two asteroid families (Flynn 1995). We may already be collecting samples of dust from *known* asteroids.

The plane of symmetry of the zodiacal cloud as a whole is inclined to the ecliptic, similarly, dust from the Themis and Koronis families forms a thin disk whose plane of symmetry must also be inclined to the ecliptic. The magnitude of this inclination is determined by the gravitational perturbation of the dust particle orbits by the planets and this varies with time with the the orbital elements of the planets. It follows from these arguments that the Earth's dust accretion rate must vary with time. This may account for the variation with time of the accretion rate of extraterrestrial ^{3}He in sedimentary layers observed by Farley (1995) and Farley & Patterson (1995).

Finally, we note that the asteroidal and cometary number densities in the zodiacal cloud will also vary with time for more obvious reasons. The asteroidal component must have been greater in the past when the mass of the asteroid belt may have been substantially greater and it will have fluctuated stochastically due to the break-up of individual asteroids and the formation of the prominent asteroid families. From time to time, the inner solar system may have been engulfed by comparatively dense waves of dust from these events. Similarly, the cometary component must have varied with time due to the capture and disintegration in the inner solar system of particularly massive comets. The effects on the Earth's climate of these extremes in the dust accretion rate may be worth investigating.

5. Interstellar Dust

Impact data from the ULYSSES dust detector at 5 AU from the sun have been interpreted as a flux of 1.5 $10^{-4}m^{-2}s^{-1}$ submicron sized interstellar dust particles arriving from ecliptic longitude 252° and latitude 2.5° (Grün *et al.*, 1994). This corresponds to a particle number density of 5.8 $10^{-15}cm^{-3}$, or equivalently, in terms of surface area per unit volume, 2.9 $10^{-23}cm^2/cm^3$. Although ULYSSES detected small particles for which gravity is not the dominant force, preliminary numerical investigations of the motion of these particles show that these small particles are focussed to produce regions of enhanced number density, albeit in different locations to those in the purely gravitational treatment. These locations are partially determined by the interplanetary magnetic field

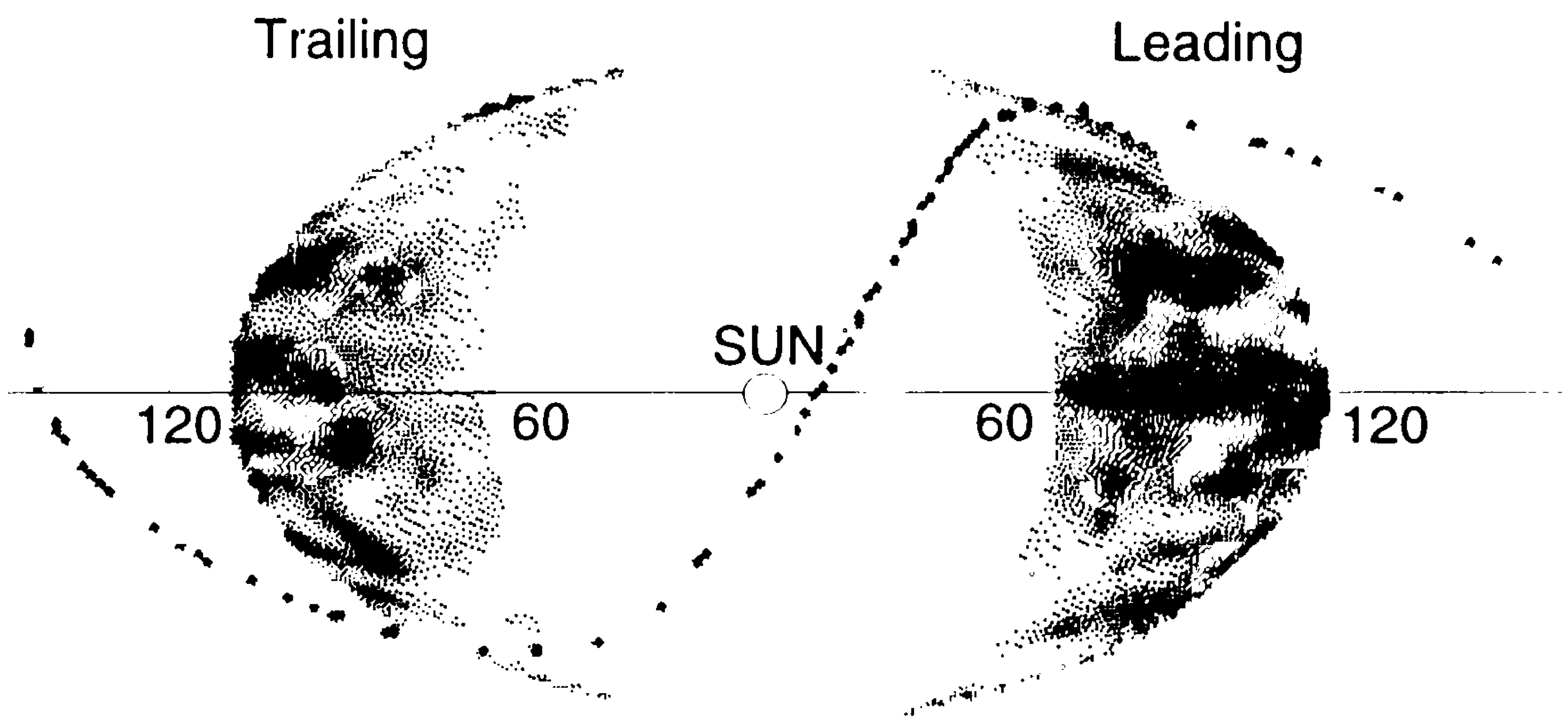

Figure 6. A sky map (Aitoff projection) of the predicted thermal emission from 0.6μm diameter particles ($\beta = 1.03$) observed in mid-December 1990 (ecliptic longitude of Earth 80°) in the COBE 12μm waveband with solar elongation angles between 60° and 120° in the trailing (left) and leading (right) directions (Grogan *et al.*, 1996a,b). The dotted line corresponds to the plane of the Galaxy. Our estimate of the maximum expected flux from an interstellar source is $\sim$ 0.1 MJy/Sr.

and will vary with the solar cycle (Gustafson, 1996). In addition, small silicate particles may also radiate strongly in the IR: a 0.6 μm radius silicate particle at 1 AU will radiate twice as much thermal energy per unit surface area in the 10 μm waveband than a 10 μm or bigger sized particle, due to a combination of a 60K temperature excess and an increased emissivity (there are strong silicate emission features at wavelengths of 10 μm and 20 μm). These considerations suggest that we may have a good chance of detecting interstellar dust particles in the DIRBE data. After removing the effects of the dust bands and the Earth's resonant circumsolar ring, we will look for characteristic signatures of interstellar dust in the residual COBE data in the 12 and 25 micron wavebands. An example of a characteristic signature is shown in Fig. 6 where we have plotted the expected flux from the putative interstellar component as seen in the 12μm waveband. Our estimate of the maximum expected flux from an interstellar source is $\sim 0.1\ MJy/Sr$ The features are very broad and by suitable coadding of data we may be able to detect a signal of this magnitude, but it will certainly not be easy. Because the interstellar signal varies with time, we should look for differences between the IRAS and COBE observations. A knowledge of the number density and size of interstellar dust particles is needed in order, for example, to determine whether cometary dust from the Kuiper belt can migrate to the inner solar system without being destroyed by collisions (Liou *et al.*, 1995b).

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