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Detecting Extended Solar System Structures With COBE

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The Cosmic Background Explorer (COBE) offers a new opportunity for the study of extended solar system structures discovered by the Infrared Astronomical Satellite (IRAS). It is expected that of these structures, Type II dust trails may be detected by the Diffuse Infrared Background Experiment (DIRBE) in which case there will be a final chance to discover their parent sources, which are as yet unknown, by immediate follow-up from groundbased imaging along the trail. Zodiacal dust bands will be easily detected at most wavelengths by DIRBE, allowing for additional analysis of their structure and geometry, as well as comparison at near-infrared wavelengths with the spectra of asteroid family members from which they are thought to derive. The other COBE experiments, as a consequence of their large beam sizes and long operating wavelengths, are not expected generally to detect these structures in the broad zodiacal emission.

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ABSTRACT

The Cosmic Background Explorer (COBE) offers a new opportunity for the study of extended solar system structures discovered by the Infrared Astronomical Satellite (IRAS). It is expected that of these structures, Type II dust trails may be detected by the Diffuse Infrared Background Experiment (DIRBE) in which case there will be a final chance to discover their parent sources, which are as yet unknown, by immediate follow-up from groundbased imaging along the trail. Zodiacal dust bands will be easily detected at most wavelengths by DIRBE, allowing for additional analysis of their structure and geometry, as well as comparison at near-infrared wavelengths with the spectra of asteroid family members from which they are thought to derive. The other COBE experiments, as a consequence of their large beam sizes and long operating wavelengths, are not expected generally to detect these structures in the broad zodiacal emission.

I. INTRODUCTION

The Cosmic Background Explorer (COBE) is the last spacebased survey instrument operating at thermal infrared wavelengths that we are likely to see through the beginning of the next century. On November 18, 1989, COBE was successfully launched into a near-polar orbit essentially identical to the orbit of its predecessor, the Infrared Astronomical Satellite (IRAS). It differs from IRAS in the beam size of its detectors and its method of scanning the sky, while covering a greater range of wavelengths from the near-IR to the radio. The satellite spin axis points away from the earth at a constant solar elongation angle of 94° (Mather, 1982).

IRAS found that the thermal background had a variety of structure over a broad range of spatial scales. On the largest scale, the infrared sky has two components: galactic and solar system (Hauser *et al.*, 1984). Galactic emission was found to contain complex structures called "infrared cirrus" due to their morphological similarity to terrestrial clouds (Low *et al.*, 1984). Solar system (zodiacal) emission was found to contain three roughly parallel bands of dust within 10° of the ecliptic, associated with collisional debris in the asteroid belt (Low *et al.*, 1984). Since then, several more pairs of dust bands have been detected within 20° of the ecliptic (Sykes, 1988a), and two additional pairs of bands have been detected at ecliptic latitudes greater than 30° (Sykes, Gautier, Good, and Low, in preparation).

An anomalously long tail was discovered in association with the comet Tempel 2 (Davies *et al.*, 1984), and was determined to be large particles spreading over a nearby portion of its orbit (Eaton *et al.*, 1984). "Dust trails" were discovered in association with the orbits of many short-period comets (Sykes *et al.*, 1986), of which Tempel 2 was the most prominent example. These contrail-like structures have characteristic widths of a few arcminutes while extending degrees to tens of degrees in length. More recently, a new variety of dust trail (Type II) has been discovered having characterstic widths from 0°.5 to 2° (Sykes, 1988a). The parent sources of Type II trails are as yet unknown.

This paper presents a detailed look at the question of whether COBE instruments are expected to detect extended solar system structures during its mission, and what new information may be provided by these detections.

II. COBE INSTRUMENTATION AND SENSITIVITIES

COBE contains three instrument packages which are described by Mather (1982, 1986, 1988) and will be briefly summarized in this section. The Differential Microwave Radiometer (DMR) consists of three sets of horn receiver pairs operating at 3.3, 5.7 and 9.6 mm. Each receiver has a beamwidth of 7° and is paired with another reciever looking 60° away on the sky, bisected by the spin axis of the satellite. This allows more than half of the sky to be mapped on a single orbit. The sensitivity at each wavelength has been estimated from a figure in Mather (1988) to be 10^{-11}, 4×10^{-12}, and 2.8×10^{-12} W/m^{2}sr, respectively, for 8 hours of integration over one year of mission time. The Far Infrared Absolute Spectrophotometer (FIRAS) is described as a "polarizing Michelson interferometric spectrometer with differential inputs" (Mather, 1986). FIRAS covers the spectral range from 0.5 to 10 mm at a resolution of $< 5\%$, but limited to 0.2 cm^{-1} (Mather, 1986). It also has a beamwidth of 7°, and points along the spin axis of the spacecraft. Since the COBE orbit will precess by $\sim 1°$/day (maintaining the COBE-earth-sun orientation), the entire sky will be covered within six months. The sensitivity of FIRAS is expected to be $\sim 10^{-9}$ W/m^{2}sr for 8 hours of observation (as above) with 5% spectral resolution.

The Diffuse Infrared Background Experiment (DIRBE) is a 10 band filter photometer, covering the spectral range from $1 - 300\mu$m. It is most important for the observation of solar system structures, because it operates at wavelengths at which thermal emission from local interplanetary dust peaks. DIRBE has a beamwidth of 0°.7 and looks out at an angle of 30° from the spin axis. As it orbits the earth, COBE will be rotating at 0.8 rpm. The DIRBE scan pattern on the sky is illustrated in Figure 1. The rotation of the spacecraft translates to an instantaneous scan rate of $\sim$ 2°.2/second (a little more than 3 beamwidths). DIRBE sensitivity across all of its detectors is estimated to be $\sim 10^{-9}$ W/m^{2}sr for $\sim$300 seconds of integration (Mather, 1982; 1988). The integration time corresponds to the average time available for observing a circular field, 0°.7 in diameter, with equal probability over the entire sky over the course of a year.

The signal-to-noise of an observation increases with increasing integration time. However, total integration time for a given location generally will be much smaller than elapsed mission time. This can be a problem in determining the detectability of solar system structures that either move and/or change position due to parallax. Therefore, with regards to DIRBE we are interested in calculating the sensitivity of the instrument for a single scan as well as for a given location multiply scanned over the course of an average orbit (which can then be extrapolated to many orbits). In the first case, the sensitivity of a DIRBE scan across a square $0\overset{\circ}{.}7 \times 0\overset{\circ}{.}7$ pixel (integration time, 0.32 sec) is 2.7×10^{-8} W/m^{2}sr. Looking at Fig. 1, spatial coverage for any given orbit is going to be greater near the edges of the path scanned by DIRBE as COBE orbits the earth. What we want to calculate is the sensitivity over a large number of orbits averaged to a single orbit for a row of $0\overset{\circ}{.}7 \times 0\overset{\circ}{.}7$ pixels spanning the swath of sky scanned by DIRBE perpendicular to the motion of the satellite. Put another way, we will calculate the average DIRBE sensitivity for a single orbit, as a function of solar elongation for a constant clock angle, taking into account the decreasing angular radius of the circle of constant solar elongation as it deviates from 90°. The result is shown in Fig. 2. For n orbits, the average sensitivity for any location in Fig. 2 is obtained by dividing by $\sqrt{n}$. However, as n gets large, one must begin to consider the effects of orbital precession, which eventually ($<$ 60 days near the ecliptic) can result in the cessation of coverage at a given location. Over the course of the mission, the "deepest" observations will be made at geocentric ecliptic latitudes greater than 64° where coverage by DIRBE essentially will be continuous.

III. EXTENDED SOLAR SYSTEM STRUCTURES

Dust Trails

Type I trails are associated with debris in the orbits of some short-period comets (Sykes *et al.*, 1986). The most prominent example of this during the IRAS mission was the Tempel 2 dust trail. This trail consists of particles in the millimeter and centimeter size range (Sykes *et al.*, 1989a). For the purpose of determining the detectability of this phenomena by COBE, we will use the Tempel 2 trail as a paradigm. Analysis of emission from the Tempel 2 trail indicates that its constituent particles have a very low albedo (Sykes, 1988b), while more recent analysis (Sykes *et al.*, 1989a) shows a small color temperature excess which may be due to a temperature gradient across the large trail particles. We will assume trail particles to behave like rapidly rotating black bodies in radiative equilibrium with incident sunlight in order to calculate their temperature. In the near-IR (from $1-10\mu$m) we will assume trail particles have an albedo of 0.07, similar to D-class asteroids in the outer asteroid belt (Lebofsky, private communication), and an albedo of zero at longer wavelengths. Since the radiant solar energy almost all lies shortward of 1 μm, this will have no significant effect on the particle equilibrium temperature. Spectral index and emissivity are assumed to be unity. The optical depth is assumed be 7.5×10^{-9}, corresponding to 2° in mean anomaly behind P/Tempel 2 in its orbit. The equivalent width of the trail at this location is 40,000 km (Sykes *et al.*, 1989a). Type II trails are assumed to have the same physical properties as the Type I trails, except that their optical depth is an order of magnitude lower than Type I trails, and the width is always sufficient to fill the DIRBE beam.

Figs. 3 and 4 shows the surface brightness densities of Type I and II trails, respectively, at heliocentric (and geocentric) distances of 1 to 4 AU. Detector sensitivities for the various COBE instruments are also shown. For observations by FIRAS and DMR, the filling factor for Type II trails assumes an angular width of $0\overset{\circ}{.}7$ at 3 AU (which translates to a width of 5.5×10^6 km). The scattered sunlight component of both Type I and II spectra in the near-IR are calculated, assuming the sun to be a 5600 K blackbody.

Zodiacal Dust Bands

The three most prominent dust band pairs (α, β, and γ) are associated with the three largest Hirayama asteroid families (Themis, Koronis, and Eos, respectively) (Sykes, 1988a). They are thought to consist of dust deriving from the subsequent comminution of debris from the disruption of the family parent bodies (e.g. Sykes and Greenberg, 1986). The dust is distributed in a squarish torus with peaks in number density near the corners, hence the appearance of pairs of bands when viewed from the earth (Sykes *et al.*, 1989b). The heliocentric latitudinal profiles assumed, normalized to peak intensity, are shown in Fig. 5.

The peak optical depth, τ, of the dust bands is calculated from an estimate of their surface brightness at 25μm as seen by IRAS (Sykes *et al.*, 1989b). To first order it is reasonable to compress the dust band tori into ribbons located at the mean locus of perihelion of the dust band particles, q, particularly since their heliocentric latitudinal profiles are independent of heliocentric distance. Particle sizes are inferred to be between 10 and 100 microns (Sykes and Greenberg, 1986), thus, in the current model, the spectral index is assumed to be flat until $\lambda \approx 50\mu$m, beyond which emissivity is allowed to decrease as $1/\lambda$. To calculate the portion of their spectrum due to scattered sunlight, particle albedos were assumed to be identical to the average albedos of the asteroid family members with which the bands are associated (calculated from Williams, 1979). Parameters for dust band particles are shown in Table 1.

Fig. 6 shows the surface brightness densities of the three principal bands, comparing them, as above, with the COBE instrument sensitivities. The α and γ band components fill the DIRBE beam, while the β band components effectively fill only half the beam. FIRAS and DMR have such large field of views that the α and β bands are not distinguished from one another. Averaging their normalized profiles (Fig. 5) over the 7° beam results in mean optical depths for the α and β bands which correspond to 0.33 and 0.29 times their respective peak optical depths (Table 1). The γ band components can be resolved from the central α and β bands with a maximum mean optical depth over the FIRAS and DMR beams of 0.7 times their peak optical depths.

IV. EXPECTATIONS

Of the COBE instruments, DMR is not expected to detect any known extended solar system structures as a consequence of its long operating wavelengths and large field of view. Similarly, FIRAS only may be able to detect zodiacal dust bands at wavelengths less than 180 microns. DIRBE will be most sensitive to both dust bands and trails due to its smaller field of view and shorter wavelength detectors.

Type I trails, such as Tempel 2, are unlikely to be detected at any wavelength by any COBE instrument. It may be possible, however, given a trail with known orbit to coadd DIRBE data in a dynamical reference frame to obtain fluxes from these structures.

Type II trails do not have known orbits therefore we cannot utilize any *a priori* knowledge to coadd DIRBE data to obtain fluxes. However, it appears that Type II trails may be detectable on images constructed from DIRBE scans collected on timescales of days, in which case there exists an opportunity to discover the parent sources of Type II trails from simultaneous groundbased observations, imaging along the observed trail path. No such opportunity will be available again with any spacebased infrared telescope planned for the future (ISO, SIRTF), since these telescopes are pointing (as opposed to survey) instruments, and are not designed to provide information on large spatial scales. Discovery of the parent bodies (if any) would allow the orbits of these trails to be determined and open up the possibility of future follow up observations by other spacebased telescopes. While we may detect Type II trails only between 8 and 30 microns, surface brightnesses at other wavelengths may be obtainable by coadding along the trail, using the $8 - 30\mu m$ observations as a guide. Fluxes at longer wavelengths would help constrain the particle size regime observed, and near-IR fluxes would allow us to compare this dust to asteroids and comets in order to further understand their origin.

The principal zodiacal dust bands (α, β, and γ) will be easily detected by DIRBE over a broad range of wavelengths on short timescales. A single days-worth of coadded images will provide not only maps of the dust bands at thermal wavelengths, but also in the near-IR. This last is particularly important in that we will be able to compare dust band near-IR spectra with that of the asteroid families from which these bands are thought to derive. In addition, we will be able to compare the near-IR spectra of the broad zodiacal background with the spectra of dust bands to further our understanding of relationship between the interplanetary dust complex and known regions of dust production in the asteroid belt.

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Table 1. Zodiacal Dust Band Parameters

Band	Family	q(AU)	Albedo	Temperature (K)	F_{peak} (W/m^{2}Hz sr)	τ
α	Themis	2.657	0.07	164	5×10^{-21}	6.5×10^{-9}
β	Koronis	2.734	0.17	156	3×10^{-20}	4.6×10^{-8}
γ	Eos	2.801	0.09	159	5×10^{-21}	7.0×10^{-9}

Figure Captions

Figure 1. The DIRBE scan pattern on a segement of sky. Open circles represent the $0\overset{\circ}{.}7$ beamsize of the instrument. The sampling rate is 3 Hz, but this is illustrative and is not related to the true sampling rate for DIRBE. Sample positions are given in terms of angular distance away from the spin axis of COBE in solar elongation. The clock angle (in degrees) refers to the position along the circle of constant solar elongation (94°) traced by the spin axis of the satellite on the sky. In this case the location of 0° clock angle is arbitrary. Spatial coverage is shown for 1, 2, and 4 orbits.

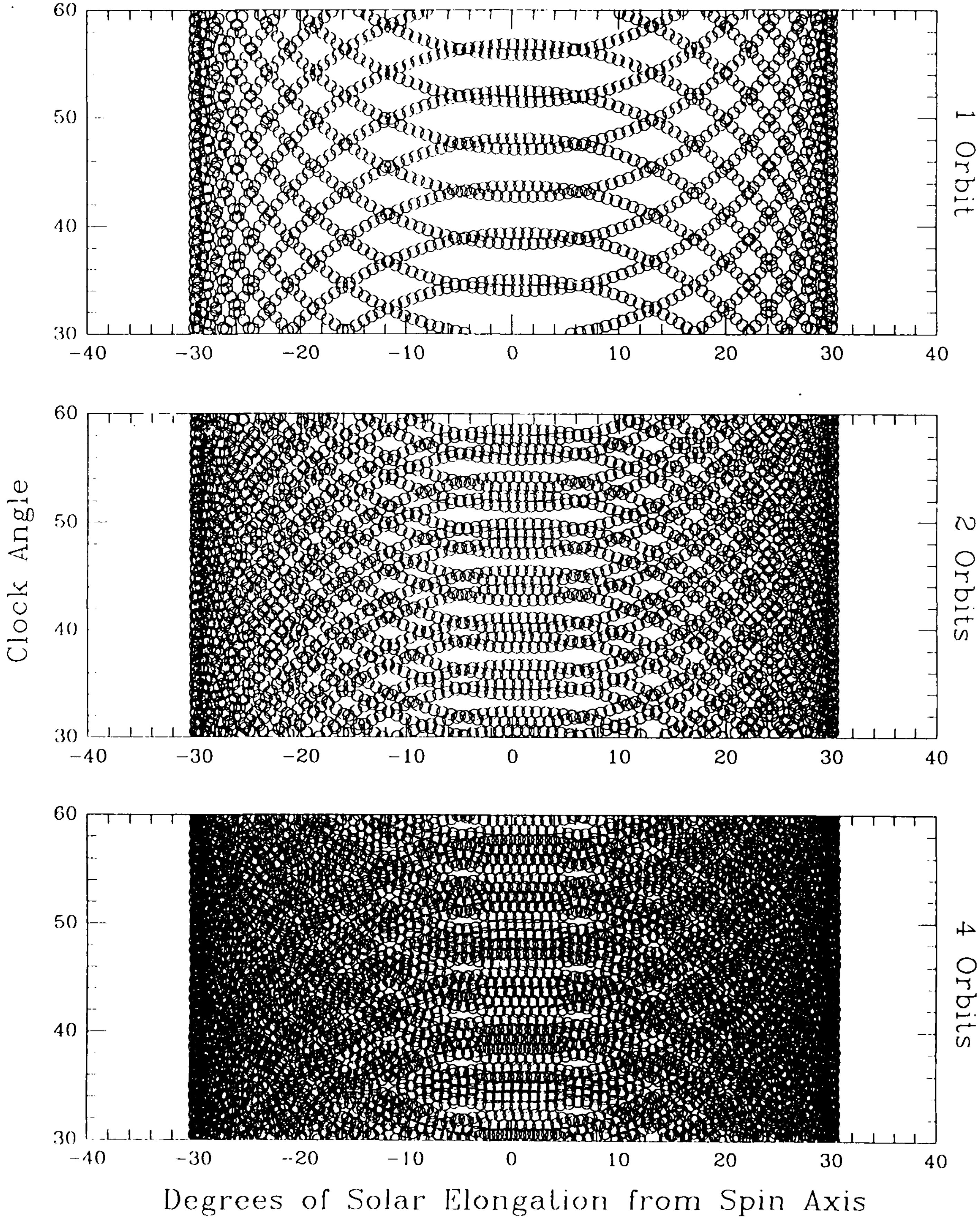
Figure 2. DIRBE sensitivity as a function of solar elongation is shown for a single orbit, averaged over all clock angles. Increasing spatial coverage away from the spin axis (which can be seen in Fig. 1), results in increasing sensitivity in the same direction, due to the increasing number of samples per bin of solar elongation, as well as the decreasing angular radius of the circle of constant solar elongation.

Figure 3. A model source function for Type I dust trails is shown which utilizes IRAS observations of the Tempel 2 dust trail as a paradigm. Trail surface brightness is diluted by the beamsizes of the various instruments. DIRBE sensitivities are given for (1) a single scan with total integration time of 0.3 seconds, (2) a single position 10° from the outer boundary of the field scanned over an orbit, observed over a mission-day (total integration time, $\sim$ 2 sec), and (3) the same location observed over 10 mission-days (total integration time, $\sim$ 18 sec). In the last two cases, DIRBE sensitivities increase toward the edge of the fields by a factor of $\sim$ 2.5. FIRAS and DMR sensitivities are for 8 hours of integration over a mission year.

Figure 4. A model source function for Type II dust trails, compared to COBE instrumental sensitivities as in Fig. 3.

Figure 5. The normalized latitudinal intensity profiles of the three principal pairs of zodaical dust bands as observed from the sun. Other dust band model parameters are given in Table 1.

Figure 6. A model source function for the zodiacal dust bands compared to COBE instrumental sensitivities. DIRBE sensitivies are described in Fig. 3. FIRAS and DMR have such large beams that the central zodiacal dust bands are not resolved.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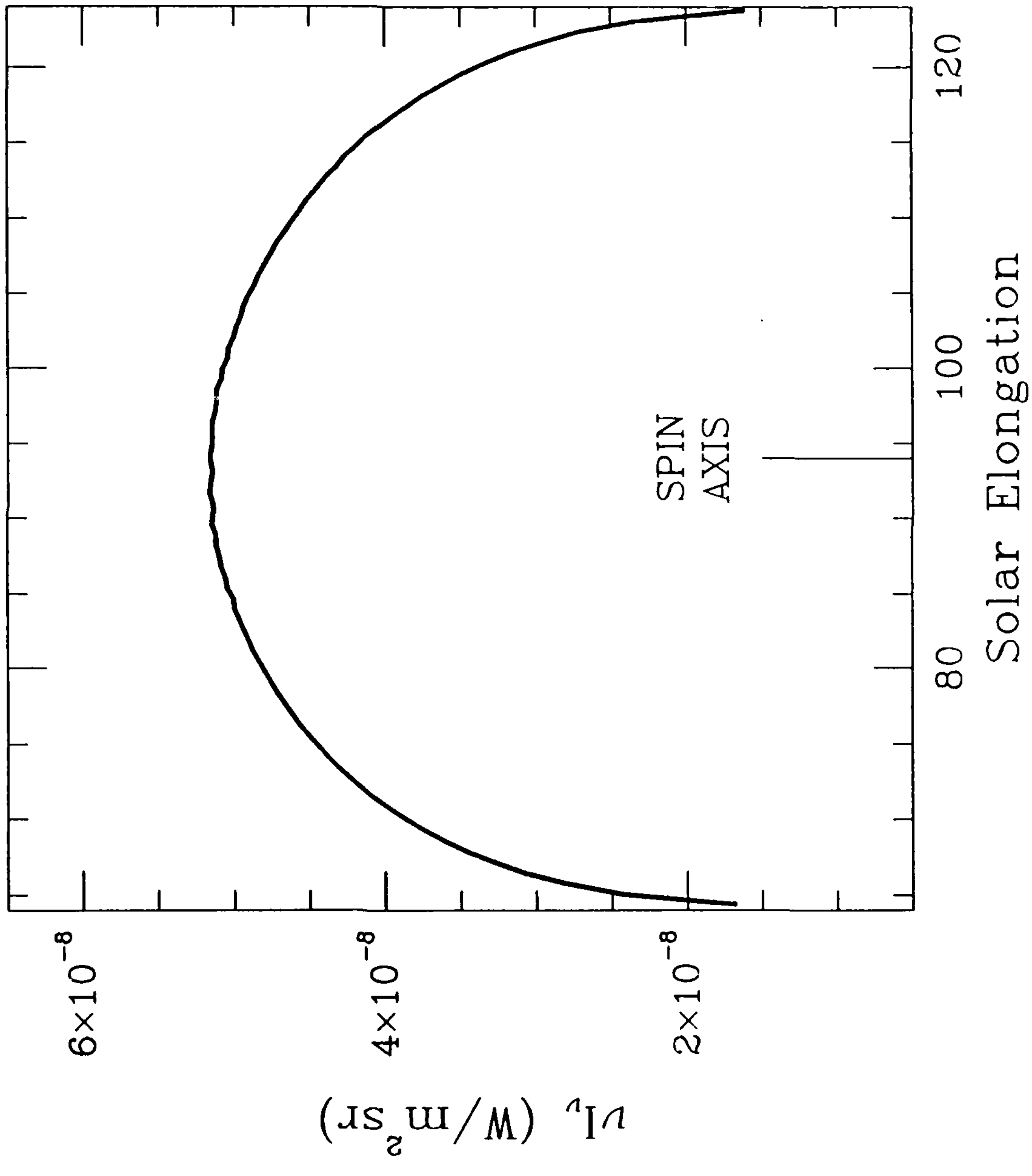
Degrees of Solar Elongation from Spin Axis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2×10⁻⁸
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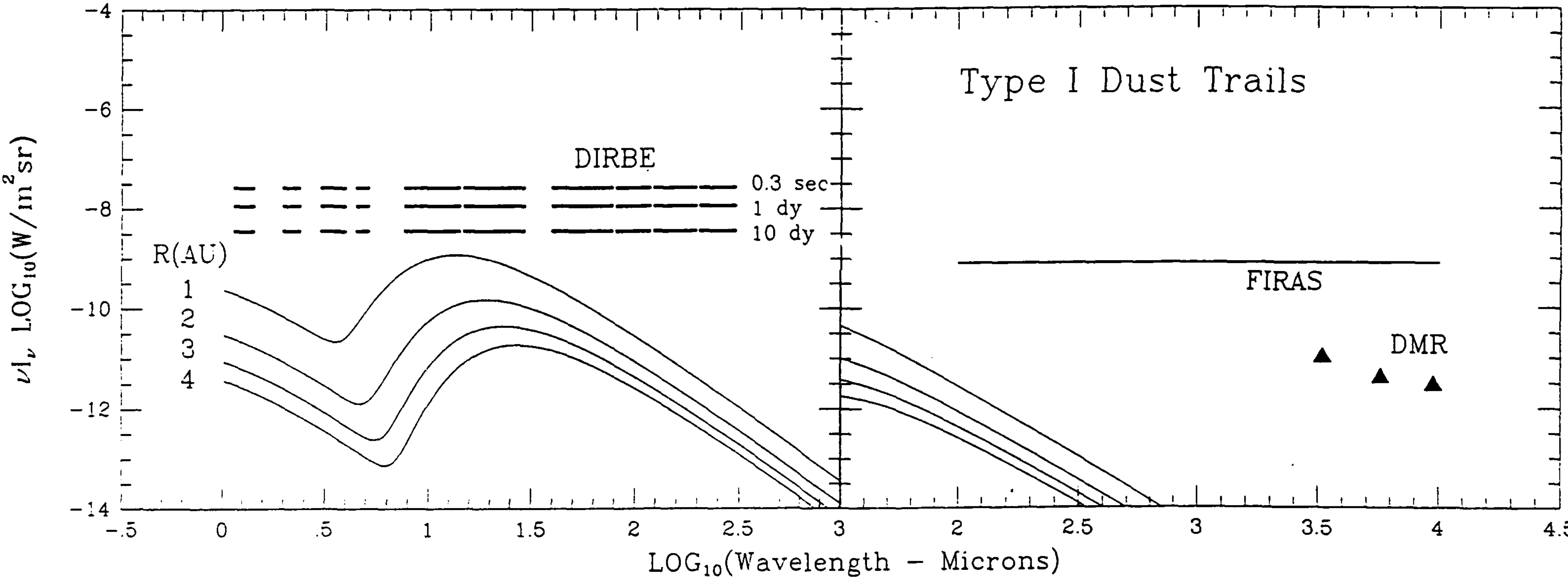
100
120
Solar Elongation
SPIN
AXIS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10 dy
R(AU)
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2
3
4
FIRAS
DMR
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-4
-6
-8
-10
-12
-14
-.5
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.5
1
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Fig 3

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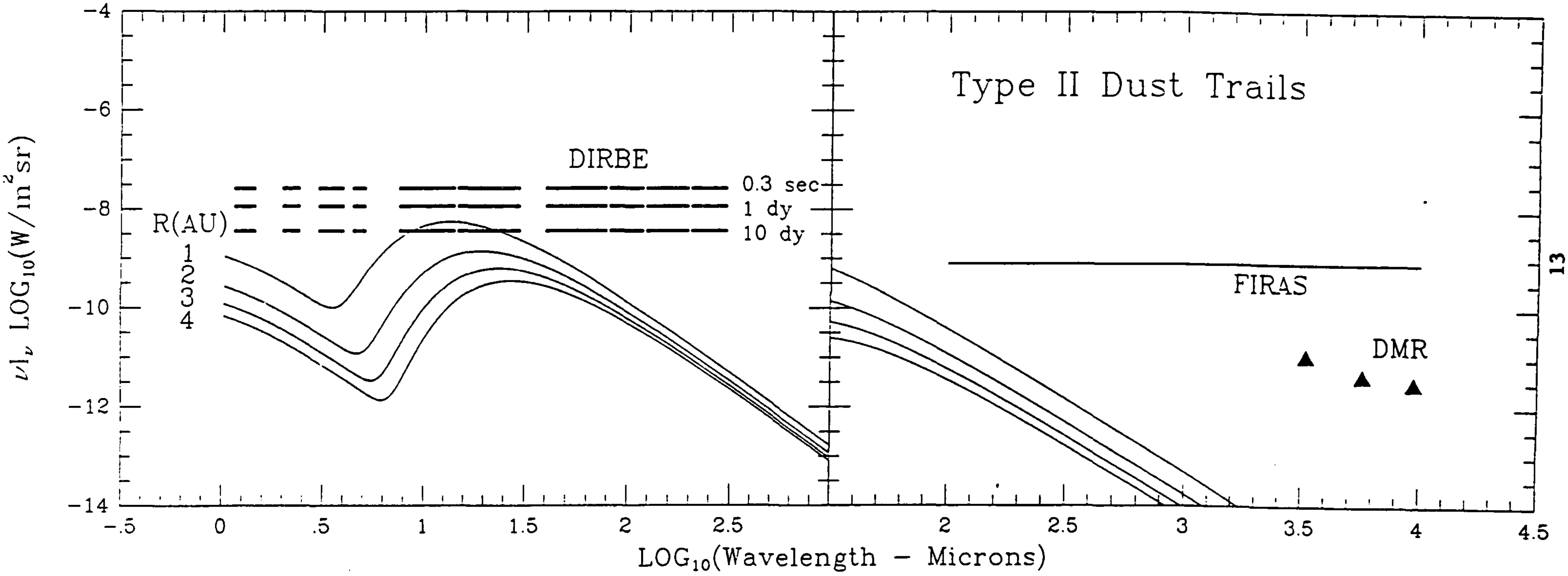
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1 dy
10 dy
R(AU)
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2
3
4
FIRAS
DMR
νI_ν LOG$_{10}$(W/m^{2}sr)
-4
-6
-8
-10
-12
-14
LOG$_{10}$(Wavelength - Microns)
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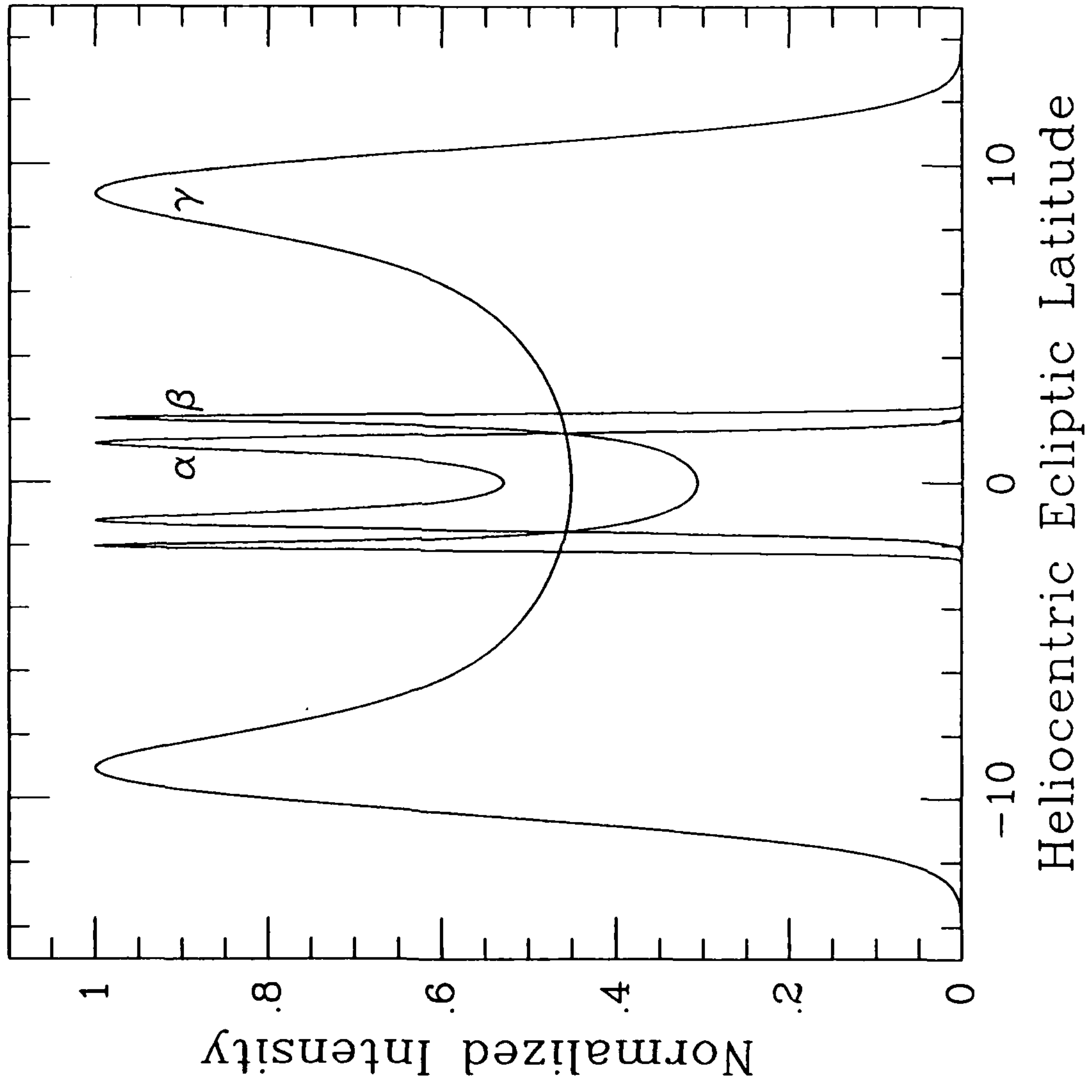
Fig 5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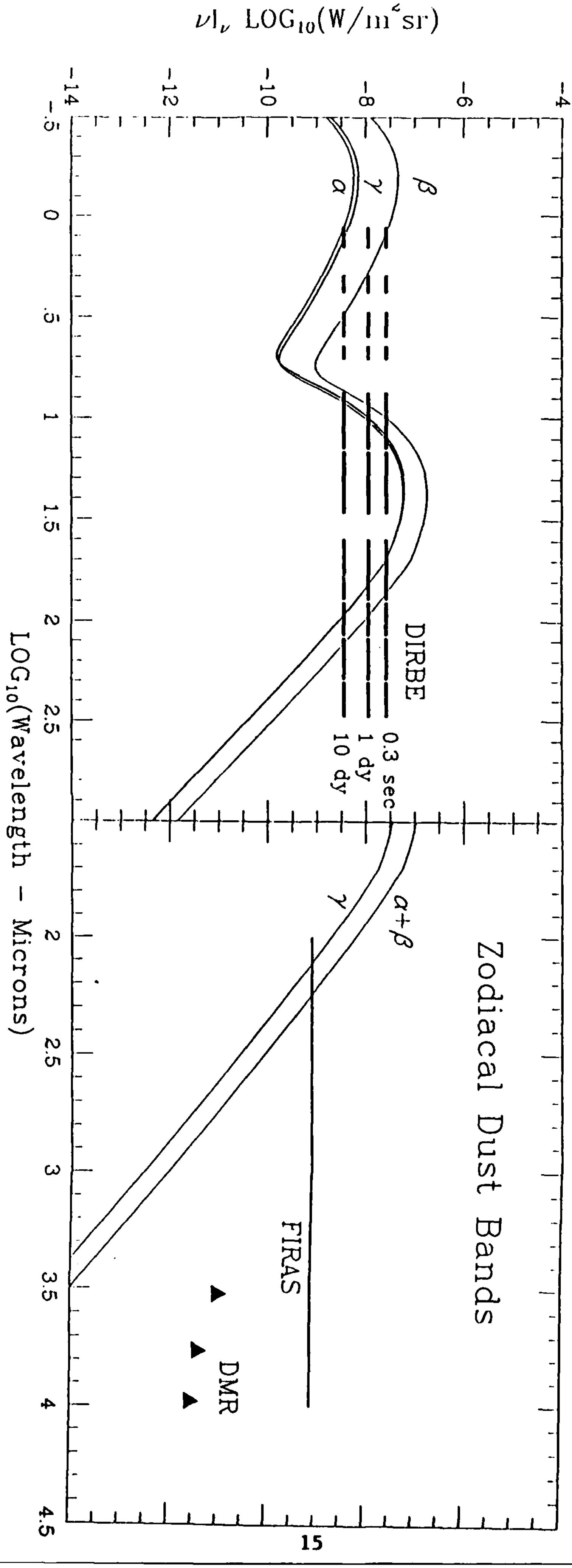
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4
4.5
LOG₁₀(Wavelength - Microns)
β
γ
α
DIRBE
0.3 sec
1 dy
10 dy
α+β
γ
FIRAS
DMR

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