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## THE NATURE OF THE MID-INFRARED BACKGROUND RADIATION IN THE GALACTIC BULGE FROM THE INFRARED TELESCOPE IN SPACE OBSERVATIONS

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### ABSTRACT

Using the Mid-Infrared Spectrometer on board the Infrared Telescope in Space, we obtained the 4.5–11.7  $\mu\text{m}$  spectra of the stellar populations and diffuse interstellar medium in the Galactic bulge ( $l \approx 8^\circ 7'$ ,  $b \approx 2^\circ 9'$ ,  $4^\circ 0'$ ,  $4^\circ 7'$ , and  $5^\circ 7'$ ). Below Galactic latitudes of  $4^\circ 0'$ , the mid-infrared background spectra in the bulge are similar to the spectra of M and K giants. The unidentified infrared emission bands (6.2, 7.7, 8.6, and 11.3  $\mu\text{m}$ ) are also detected in these regions and likely arise from the diffuse interstellar medium in the disk. Above Galactic latitudes of  $4^\circ 0'$ , the mid-infrared background spectra are similar to the spectra of those oxygen-rich evolved stars with high mass-loss rates detected by *IRAS*. One likely interpretation is that this background emission arises predominantly from those stars with very low luminosities that have not been detected by *IRAS*. The age for such low-luminosity evolved stars could be 15 Gyr, and the existence of a large number of evolved stars with high mass-loss rates in the bulge has a significant impact on our understanding of the stellar content in the Galactic bulge.

*Subject headings:* Galaxy: stellar content — infrared: stars — stars: AGB and post-AGB

### 1. INTRODUCTION

The Galactic bulge is characterized by a diversity of stellar populations: main-sequence stars, K and M giants, asymptotic giant branch (AGB) stars, planetary nebulae, and white dwarfs. The bulge ages derived from these different stellar populations have big discrepancies. Studies of the RR Lyrae variables, the main-sequence turnoff, the luminosity of M giants, the mass of planetary nebulae, the characteristics of Mira variables, and AGB stars with large mass-loss rates give bulge ages ranging from 5 to 15 Gyr (see, e.g., Gratton, Tornambè, & Ortolani 1986; Terndrup 1988; Frogel & Whitford 1987; Kinman, Feast, & Lasker 1988; Feast & Whitelock 1987; van der Veen & Habing 1990; 1 Gyr =  $10^9$  yr). Knowing the stellar populations and their properties in the Galactic bulge would not only provide useful information on the bulge formation but would also help us to construct stellar synthesis models of spheroidal galaxies, for which only the integrated light can be observed. From the observations of the Diffuse Infrared Background Experiment (DIRBE) on board the *Cosmic Background Explorer* (*COBE*), Arendt et al. (1994) found that the near-infrared background radiation in the Galactic bulge is similar to that of late-K and M giants. The *Infrared Astronomical Satellite* (*IRAS*) detected a large number of mid-infrared bright stars in the Galactic bulge (Habing et al. 1985); however, the *IRAS* did not have the sensitivity to detect those mid-infrared faint stars that could dominate the mid-infrared background radiation in the Galactic bulge. Furthermore, the *IRAS* Sky Survey Atlas (ISSA; Wheelock et al. 1994) flux densities at 12 and 25  $\mu\text{m}$  cannot provide unambiguous color data to study the stellar populations, which are likely to be contaminated by the interstellar unidentified infrared (UIR) bands and small grains emission, respectively. Thus, spectrophotometric or high spatial resolution pho-

tometric observations in the mid-infrared band (e.g., 4–25  $\mu\text{m}$ ) are required for the study of the mid-infrared background radiation in the Galactic bulge. In this Letter, we present results from our mid-infrared (4.5–11.7  $\mu\text{m}$ ) spectrophotometric observations in parts of the Galactic bulge, and we also discuss the nature of the stellar population there that dominates the mid-infrared background radiation. Throughout our Letter, we assume a Sun-to-Galactic center distance of 8.5 kpc.

### 2. OBSERVATIONS AND RESULTS

The Mid-Infrared Spectrometer (MIRS) was one of the four science focal-plane instruments that flew aboard the orbiting Infrared Telescope in Space (IRTS). This telescope was a joint Japanese Space Agency (ISAS)/NASA project that was launched on 1995 March 18 and surveyed  $\sim 7\%$  of the sky over the course of its 26 day mission life (Murakami et al. 1996). The MIRS had a beam size of  $8' \times 8'$  and operated over a wavelength range of 4.5–11.7  $\mu\text{m}$  with a resolution of 0.23–0.36  $\mu\text{m}$  (Roellig et al. 1994). During the course of its mission, the MIRS observed parts of the Galactic bulge, and we present here the spectra at  $l \approx 8^\circ 7'$ ,  $b \approx 2^\circ 9'$ ,  $4^\circ 0'$ ,  $4^\circ 7'$ , and  $5^\circ 7'$ . The absolute calibration is about 10% in this preliminary phase (see Tanabé et al. 1997 for details of the MIRS calibration). Selected regions were chosen for this study that did not include bright *IRAS* point sources, and the zodiacal background emission has been subtracted. To subtract the zodiacal background, we first selected zodiacal background spectra that were observed by the MIRS at regions (far away from the Galactic plane) that have the same ecliptic latitudes but different longitudes as those we chose in the bulge. We then corrected the brightness of these observed zodiacal background spectra in order to match the zodiacal brightness at the same solar elongations as those in the bulge by using a *IRAS* zodiacal cloud model (Wheelock et al. 1994). Finally, these model zodiacal background spectra were subtracted from our selected bulge

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TABLE 1

EXTINCTIONS IN THE CLOSEST DIRBE PIXELS TO OUR OBSERVED POSITIONS

| Galactic Coordinates<br>( <i>l</i> , <i>b</i> ) | (8°78, 2°71) | (8°70, 4°16) | (8°37, 4°72) | (8°62, 5°60) |
|---|--------------|--------------|--------------|--------------|
| $\tau_{1.25\ \mu\text{m}}$ .....                | 0.415        | 0.247        | 0.200        | 0.122        |
| $\tau_{4.9\ \mu\text{m}}$ .....                 | 0.034        | 0.020        | 0.016        | 0.009        |
| $\tau_{\text{silicate}}$ .....                  | 0.096        | 0.057        | 0.046        | 0.028        |

spectra (bulge + zodiacal emission). The zodiacal cloud emission at 12  $\mu\text{m}$  in our selected regions is between 5 and 9 times higher than the bulge emission there.

We estimated the extinctions to our observed regions for the purpose of checking whether or not extinction corrections on our spectra are necessary. Based on the DIRBE/COBE data, Arendt et al. (1994) found that the unreddened near-infrared colors in the Galactic bulge are similar to those of late-K and M giants. Thus, the optical depth at 1.25  $\mu\text{m}$  can be estimated as

$$\tau_{1.25\ \mu\text{m}} = \frac{\ln [(I_{1.25\ \mu\text{m}}/I_{2.2\ \mu\text{m}})/0.95]}{-0.603}, \quad (1)$$

where  $I$  is the measured DIRBE intensity, 0.95 is the ratio of the flux densities at 1.25 and 2.2  $\mu\text{m}$  of the unreddened late-K and M giants, and  $-0.603 = A_{2.2\ \mu\text{m}}/A_{1.25\ \mu\text{m}} - 1$  is the

reddening between 1.25 and 2.2  $\mu\text{m}$  and is adapted from the Rieke & Lebofsky (1985) interstellar extinction law. Based on equation (1) and the final DIRBE/COBE mission-averaged pass 3B data with zodiacal light removed, as described by Kelsall et al. (1998), the  $\tau_{1.25\ \mu\text{m}}$  are calculated by assuming that the extinction lies in front of the emission sources along the line of sight. It should be noted that this assumption minimizes the total line-of-sight extinction derived from the reddening. Table 1 summarizes the  $\tau_{1.25\ \mu\text{m}}$  as derived in the closest DIRBE pixels to our observed positions. The size of a DIRBE pixel is  $0^{\circ}32 \times 0^{\circ}32$ , and the size of a DIRBE beam is  $0^{\circ}7 \times 0^{\circ}7$ . With these derived  $\tau_{1.25\ \mu\text{m}}$  values, the optical depths at 4.9  $\mu\text{m}$  ( $\tau_{4.9\ \mu\text{m}}$ ) and 10  $\mu\text{m}$  silicate ( $\tau_{\text{silicate}}$ ) are calculated from the Rieke & Lebofsky (1985) extinction law and are also summarized in Table 1. In Table 1, the extinctions at/or around our observed positions are small (1%–10% in the MIRS spectral range); therefore, extinction corrections on our spectra were not applied in the following analysis.

Figure 1 shows the observed spectra of the Galactic bulge at our selected positions. In Figures 1a and 1b, it can be seen that the mid-infrared background spectra in the bulge at Galactic latitudes of 2°9 and 4°0 are similar to those of the M and K giants observed by MIRS, which do not have thick dust shells and their mid-infrared emission mostly arises from the stellar photospheres at temperatures of a few thousand kelvins (Yamamura et al. 1996, 1997). The UIR emission bands (6.2,

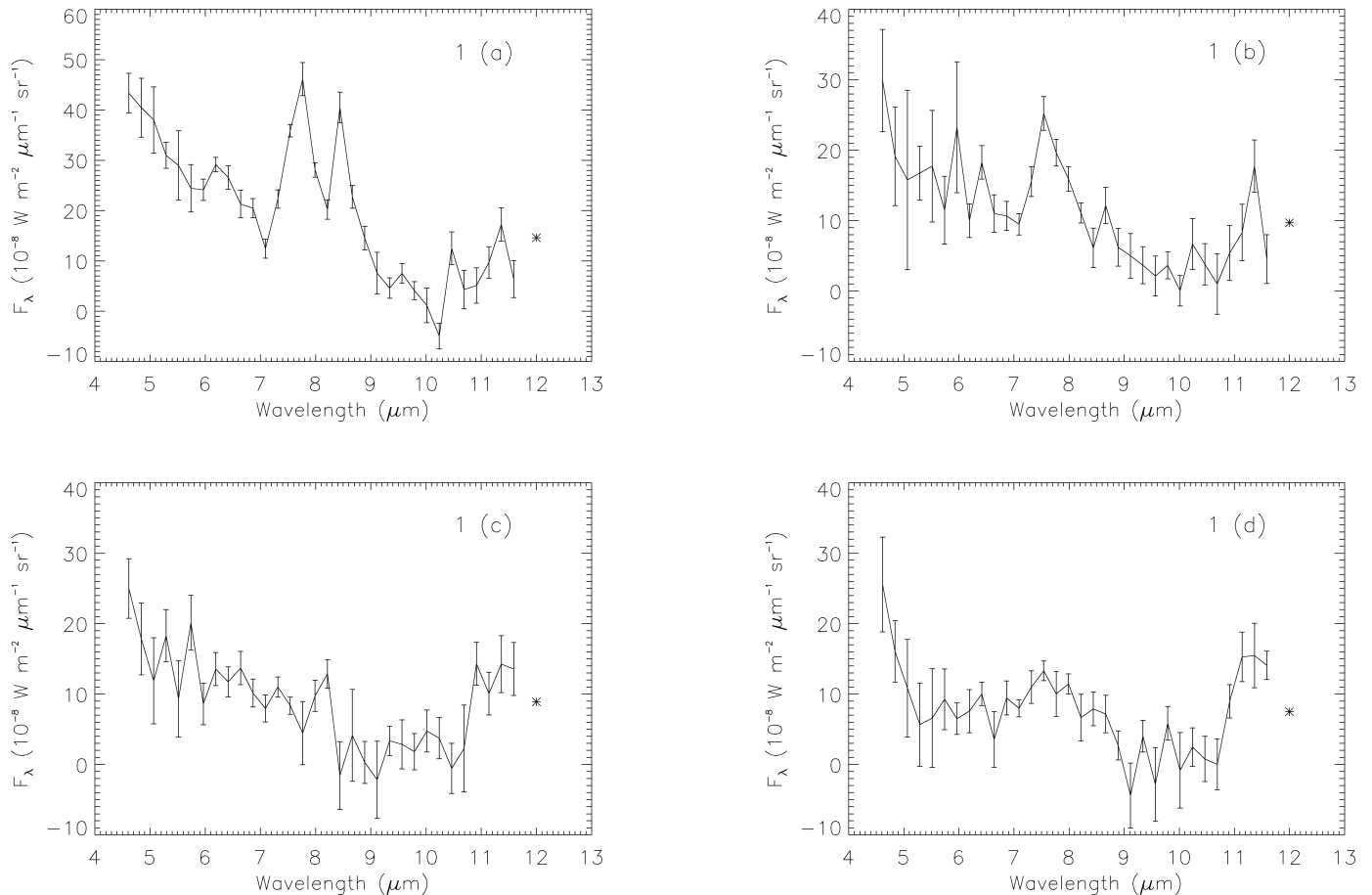


FIG. 1.—The observed MIRS spectra at (a)  $l = 8^{\circ}77$ ,  $b = 2^{\circ}88$ , (b)  $l = 8^{\circ}69$ ,  $b = 4^{\circ}05$ , (c)  $l = 8^{\circ}45$ ,  $b = 4^{\circ}68$ , and (d)  $l = 8^{\circ}67$ ,  $b = 5^{\circ}74$ . The measured fluxes have been averaged in units of 5 s, and this resulted in an effective beam size of  $8' \times 20'$ . The asterisk is the ISSA 12  $\mu\text{m}$  flux. The bandpass of the IRAS 12  $\mu\text{m}$  channel was 8–15  $\mu\text{m}$ , and the resolution of the ISSA 12  $\mu\text{m}$  data is  $4'$ . The total flux from the IRAS point sources contributes no more than 10% of the ISSA 12  $\mu\text{m}$  flux in these regions.

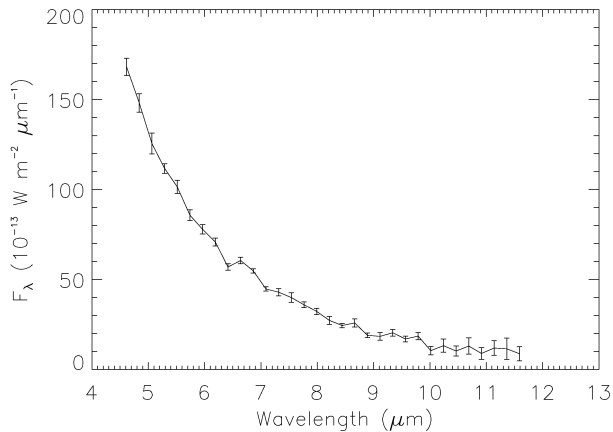


FIG. 2.—The spectrum of Z UMa (M5 giant) observed by MIRS and adapted from Yamamura et al. 1997.

7.7, 8.6, and 11.3  $\mu\text{m}$ ) are also detected in these regions, and they likely arise from the diffuse interstellar medium in the disk (see, e.g., Onaka et al. 1996 for the observations of interstellar UIR emission bands in the Galactic plane). Figure 2 shows the spectrum of one of the M giants observed by MIRS, and it can be seen that its spectral shape is similar to the stellar spectra in Figures 1a and 1b. On the other hand, in Figures 1c and 1d, the mid-infrared background spectra at Galactic latitudes of  $4^\circ 7'$  and  $5^\circ 7'$  are similar to those of oxygen-rich AGB stars with thick dust shells, which have a typical silicate absorption feature at 10  $\mu\text{m}$  (see, e.g., Forrest et al. 1978 and Herman et al. 1984). For comparison, Figure 3 shows the spectrum of an oxygen-rich AGB star with the silicate absorption feature observed by MIRS. Even though the MIRS spectra in Figures 1c and 1d are a bit noisy, the silicate absorption feature is real. This is because the depression in the 8–11  $\mu\text{m}$  range in both of the spectra is approximately  $-75\% \pm 25\%$ , which is larger than the 10% calibration uncertainty of the MIRS. Furthermore, these silicate absorption features should not arise from the line-of-sight extinction, because the optical depths of the interstellar silicate absorption at/or around our observed positions are much less than 1 (see Table 1). The *IRAS* Sky Survey Atlas (ISSA) 12  $\mu\text{m}$  fluxes are also shown in Figure 1. In Figures 1a and 1b, the ISSA 12  $\mu\text{m}$  flux seems to be due mostly to UIR emission bands at 7.7, 8.6, and 11.3  $\mu\text{m}$ . On the other hand, the ISSA 12  $\mu\text{m}$  flux in Figures 1c and 1d is due mostly to circumstellar dust emission.

### 3. DISCUSSION

#### 3.1. Evolved Stars as Seen by *IRAS*

Habing (1987, hereafter Habing87) has shown that the *IRAS* 25/12  $\mu\text{m}$  flux ratio for *IRAS* point sources in the Galactic bulge can be used to select those late-type stars with high mass-loss rates in order to produce an estimate of the bulge age. Habing87 assumed that the total integrated flux of these stars can be represented as  $3\nu F_\nu(12 \mu\text{m})$ , where  $\nu = 2.5 \times 10^{13}$  Hz and  $F_\nu(12 \mu\text{m})$  is the measured *IRAS* 12  $\mu\text{m}$  flux density. The factor of 3 is defined as the infrared bolometric correction (see van der Veen & Breukers 1989). Habing87 proposed that these selected objects in the bulge region are Mira and OH/IR stars and found that they have a luminosity function that peaks at  $\sim 4000 L_\odot$ . For an AGB star with a luminosity of  $4000 L_\odot$ , Habing87 estimated that it has an initial mass of  $1.7 M_\odot$  and

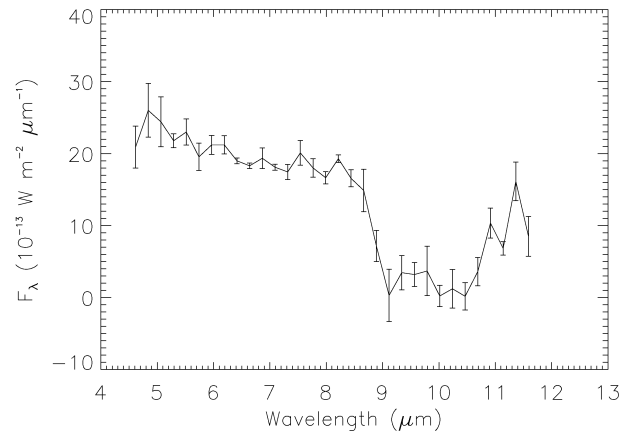


FIG. 3.—The spectrum of OH 138.0+7.2 (an OH/IR star) observed by MIRS.

an age of  $\sim 1.3$  Gyr (from zero-age main sequence to the first giant branch,  $Z = 0.04$ , and  $Y = 0.3$ )—much lower than that estimated from observations in Baade's window ( $\geq 10$  Gyr) (see, e.g., Frogel 1988). A later study by van der Veen & Habing (1990), with more accurate selection criteria to select AGB stars from the *IRAS* data, found that the AGB stars with high mass-loss rates in the Galactic bulge have a luminosity function that peaks at  $\sim 5500 L_\odot$ . However, with better knowledge of the evolution of AGB stars, they found that the initial mass of AGB stars with  $5500 L_\odot$  is only  $1.4 M_\odot$  and that their age is 7–15 Gyr ( $Z = 0.04$  and  $Y = 0.2$ ). Harmon & Gilmore (1988), however, have found that the AGB stars as seen by *IRAS* in the bulge have a luminosity function that peaks at  $\sim 6000$  and  $7600 L_\odot$ . They estimated that these AGB stars have initial masses of 1.3 and  $1.5 M_\odot$  and ages of 10 and 5 Gyr ( $Z = 0.1$  and  $Y = 0.25$ ), respectively. From the above *IRAS* studies, the ages of AGB stars in the Galactic bulge have a large range of 5–15 Gyr. The main reason for this large range is the high uncertainty of the mass-loss history of these AGB stars in the bulge.

#### 3.2. Evolved Stars as Seen by *IRTS*

In Figures 1c and 1d, the mid-infrared background spectra at Galactic latitudes of  $4^\circ 7'$  and  $5^\circ 7'$  are similar to the spectra of evolved stars with circumstellar silicate absorption. Therefore, the stars in these regions that produce the mid-infrared background emission are very similar to those AGB stars with large mass-loss rates detected by *IRAS*. Since there are no bright *IRAS* 12  $\mu\text{m}$  point sources in these bulge regions that can account for the flux levels measured by the MIRS, one likely interpretation of this background emission is that it arises predominantly from AGB stars with large mass-loss rates, but with very low luminosities that could not have been detected by *IRAS*. From the *IRAS* Faint Source and Point Source Catalogs, we find that there are less than 50 detected *IRAS* point sources per square degree at our observed positions in Figures 1c and 1d, which is less than the threshold value ( $50 \text{ deg}^{-2}$ ) of the *IRAS* confusion limit at 12  $\mu\text{m}$  (*IRAS* Explanatory Supplement; Beichman et al. 1988). Therefore, the *IRAS* observations at our observed positions in Figures 1c and 1d are not confusion limited. Away from confused regions of the sky, the sensitivity of *IRAS* at 12  $\mu\text{m}$  is 0.5 Jy (Beichman et al. 1988). For an upper limit estimate of the stellar properties (e.g., luminosity and initial mass), we assume that each of these AGB stars has a 12  $\mu\text{m}$  flux density of 0.5 Jy and that this flux density cor-

responds to a luminosity of  $850 L_{\odot}$  in the bulge. From the MIRS spectra in Figures 1c and 1d, the flux level of 30 Jy at  $11.7 \mu\text{m}$  implies that there are at least 60 AGB stars in the  $8' \times 8'$  MIRS beam (or  $\sim 3375$  stars per square degree), each averaging  $\sim 850 L_{\odot}$  (cf. the *Infrared Space Observatory* survey observations of the Galactic plane at  $l \approx -45^{\circ}$  and  $b \approx 0^{\circ}$  by Péroul et al. 1996, where they detected  $\sim 1500$  M and K giants per square degree at  $15 \mu\text{m}$ ). Comparing the spectra in Figure 1, it can be seen that M and K giants dominate the mid-infrared emission in the lower latitudes of the bulge (Figs. 1a and 1b), while low-luminosity AGB stars with large mass-loss rates dominate the mid-infrared emission in the higher latitudes (Figs. 1c and 1d). These differences indicate that the bulge has a gradient in the stellar populations such that the relative numbers of M and K giants to AGB stars decrease with increasing latitude.

The relation between the maximum luminosity in the late stage of the AGB star and its initial mass were discussed by Iben & Renzini (1983) and can be written as

$$L_{\text{max}} = 59250[0.53\eta^{-0.082} + 0.15(M_i - 1)\eta^{-0.35} - 0.495], \quad (2)$$

where  $L_{\text{max}}$  is the maximum luminosity (in unit of  $L_{\odot}$ ) reached along the AGB evolution, the parameter  $\eta$  is proportional to the mass-loss rate of the star and has a value of unity with a factor of 3 uncertainty ( $\frac{1}{3} \leq \eta \leq 3$ ), and  $M_i$  is the initial mass (in units of solar mass) of the AGB star. Here we choose  $\eta = 1$  for estimates of the initial mass of our detected AGB

stars, and from equation (2) we find that these AGB stars have initial masses of  $0.86 M_{\odot}$ . The age of these  $0.86 M_{\odot}$  stars can be estimated if their metallicities are known; unfortunately, however, our observations presented here do not provide any useful information about their metallicities. Just for a comparison with the past *IRAS* studies mentioned in the previous section, we assume that these AGB stars have metallicities of 1.9 times solar ( $Z = 0.03$ ). From the stellar evolution model of Vandenberg & Laskarides (1987), the age of a  $0.86 M_{\odot}$  star with  $Z = 0.03$  and  $Y = 0.35$  is  $\sim 15$  Gyr.

In summary, the major results of this Letter are as follows: (1) there is a gradient in the stellar populations of the Galactic bulge, where the relative numbers of M and K giants to AGB stars decrease with increasing latitude, and (2) there could be a lot of ( $3375 \text{ deg}^{-1}$ ) old age ( $\sim 15$  Gyr) and low-luminosity ( $\sim 850 L_{\odot}$ ) AGB stars with large mass-loss rates at the higher latitude field of the bulge.

We are grateful to Rick Arendt for providing the optical depths at  $1.25 \mu\text{m}$  summarized in Table 1 and for the many useful comments that helped in improving the Letter. We thank Martin Cohen for providing the calibrated spectra of standard stars for the calibration of MIRS. We also thank IPAC for their help in the pointing reconstruction of the IRTS and the entire IRTS team for their efforts in ensuring the success of the IRTS mission. I. Y. is supported by the JSPS Research Fellowships for Young Scientists. The *COBE* data sets were developed by the NASA Goddard Space Flight Center under the guidance of the *COBE* Science Working Group and were provided by the NSSDC.

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