The nature of the mid-infrared background radiation in the galactic bulge from the IRTS observations
Chan, K.W.; Roellig, T.L.; Onaka, T.; Yamamura, I.; Tanabe, T.

Published in:
Astrophysical Journal

DOI:
10.1086/311592

Citation for published version (APA):
THE NATURE OF THE MID-INFRARED BACKGROUND RADIATION IN THE GALACTIC BULGE FROM THE INFRARED TELESCOPE IN SPACE OBSERVATIONS

KIN-WING CHAN AND T. L. ROELLIG
NASA Ames Research Center, MS 245-6, Moffett Field, CA 94035; kwc@ssa1.arc.nasa.gov, roellig@ssa1.arc.nasa.gov

T. ONAKA AND I. YAMAMURA1
Department of Astronomy, University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan; onaka@astron.s.u-tokyo.ac.jp, yamamura@astro.uva.nl

AND

T. TANABÉ
Institute of Astronomy, University of Tokyo, Mitaka, Tokyo 181-8588, Japan; ttanable@mtk.ioa.s.u-tokyo.ac.jp

Received 1998 May 15; accepted 1998 July 27; published 1998 August 24

ABSTRACT

Using the Mid-Infrared Spectrometer on board the Infrared Telescope in Space, we obtained the 4.5–11.7 μm spectra of the stellar populations and diffuse interstellar medium in the Galactic bulge (l ≈ 87°, b ≈ 2°9, 4°0, 4°7, and 5°7). Below Galactic latitudes of 4°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 μm) are also detected in these regions and likely arise from the diffuse interstellar medium in the disk. Above Galactic latitudes of 4°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 characteristics of Mira variables, and 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, TornambeÁ, & Ortolani 1986; Terndrup 1988; Frogel & Whitford 1987; Kinman, Feast, & Amsterdam, Kruislaan 403, NL-1098 SJ Amsterdam, the Netherlands.

of planetary nebulae, the characteristics of Mira variables, and

assumption a Sun±to±Galactic center distance of 8.5 kpc.

tometric observations in the mid-infrared band (e.g., 4–25 μm)

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 (JAS)/NASA project that was launched on 1995 March 18 and surveyed ~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′ × 8′ and operated over a wavelength range of 4.5–11.7 μm with a resolution of 0.23–0.36 μm (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 ≈ 87°, b ≈ 2°9, 4°0, 4°7, and 5°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
TABLE 1
EXTINCTIONS IN THE CLOSEST DIRBE PIXELS TO OUR OBSERVED POSITIONS

<table>
<thead>
<tr>
<th>Galactic Coordinates</th>
<th>(l, b)</th>
<th>(8’78, 2°71)</th>
<th>(8°70, 4°16)</th>
<th>(8°37, 4°72)</th>
<th>(8°62, 5°60)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{1.25 \mu m}$</td>
<td>0.415</td>
<td>0.247</td>
<td>0.200</td>
<td>0.122</td>
<td></td>
</tr>
<tr>
<td>$\tau_{4.9 \mu m}$</td>
<td>0.034</td>
<td>0.020</td>
<td>0.016</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>$\tau_{\text{silicate}}$</td>
<td>0.096</td>
<td>0.057</td>
<td>0.046</td>
<td>0.028</td>
<td></td>
</tr>
</tbody>
</table>

spectra (bulge + zodiacal emission). The zodiacal cloud emission at 12 $\mu m$ 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/COBÉ 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 $\mu m$ can be estimated as

$$\tau_{1.25 \mu m} = \frac{\ln [I_{1.25 \mu m}/I_{2.2 \mu m}] / 0.95}{-0.603}$$

(1)

where $I$ is the measured DIRBE intensity, 0.95 is the ratio of the flux densities at 1.25 and 2.2 $\mu m$ of the unreddened late-K and M giants, and $-0.603 = A_{2.2 \mu m}/A_{1.25 \mu m} - 1$ is the reddening between 1.25 and 2.2 $\mu m$ and is adapted from the Rieke & Lebofsky (1985) interstellar extinction law. Based on equation (1) and the final DIRBE/COBÉ mission–averaged pass 3B data with zodiacal light removed, as described by Kelsall et al. (1998), the $\tau_{1.25 \mu m}$ 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 $\tau_{1.25 \mu m}$ as derived in the closest DIRBE pixels to our observed positions. The size of a DIRBE pixel is 0:32 x 0:32, and the size of a DIRBE beam is 0:7 x 0:7. With these derived $\tau_{1.25 \mu m}$ values, the optical depths at 4.9 $\mu m$ ($\tau_{4.9 \mu m}$) and 10 $\mu m$ 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,
7.7, 8.6, and 11.3 μm) 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°7 and 5°7 are similar to those of oxygen-rich AGB stars with thick dust shells, which have a typical silicate absorption feature at 10 μm (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 μm range in both of the spectra is approximately −75% ± 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 μm fluxes are also shown in Figure 1. In Figures 1a and 1b, the ISSA 12 μm flux seems to be due mostly to UIR emission bands at 7.7, 8.6, and 11.3 μm. On the other hand, the ISSA 12 μm 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 μm 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 $3vF_v(12 \, \mu m)$, where $v = 2.5 \times 10^{13}$ Hz and $F_v(12 \, \mu m)$ is the measured IRAS 12 μm 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 ∼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 an age of ∼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 (≥10 Gyr) (see, e.g., Frogen 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 ∼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 ~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°7 and 5°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 μm 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 deg^-2) of the IRAS confusion limit at 12 μm (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 μm 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 μm 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 $\mu$m implies that there are at least 60 AGB stars in the 8' × 8' MIRS beam (or ~3375 stars per square degree), each averaging ~$850 \, L_{\odot}$ (cf. the Infrared Space Observatory survey observations of the Galactic plane at $l \approx -45^\circ$ and $b \approx 0^\circ$ by Pérolt et al. 1996, where they detected ~1500 M and K giants per square degree at 15 $\mu$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

$$L_{\text{max}} = 59250(0.53\eta^{-0.082} + 0.15(M_1 - 1)\eta^{-0.35} - 0.495),$$  \hspace{1cm} (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 ($1 \leq \eta \leq 3$), and $M_1$ 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 ~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 deg$^{-2}$) old age (~15 Gyr) and low-luminosity (~$850 \, L_{\odot}$) 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 $\mu$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.

REFERENCES

Iben, I., Jr., & Renzini, A. 1983, ARA&A, 21, 271
Yamamura, I., & IRTS Team. 1997, in ASP Conf. Ser. 124, Diffuse Infrared Radiation and the IRTS, ed. H. Okuda, T. Matsumoto, & T. Roellig (San Francisco: ASP), 72