Far evolved AGB stars in the galactic bulge

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Abstract. We have selected 37 objects from the IRAS Point Source Catalogue, that lie in the general direction of the galactic bulge and that have the colours of stars with thick circumstellar dust shells. From the European Southern Observatory we have made repeatedly over the last four years infrared photometric observations between 2 and 13 μm.

All sources, minus one, have overall spectra typical of OH/IR stars. The repeated observations show that the luminosity of each source varies in time; periods of about 700 days are typical and amplitudes of ~1 mag. Comparison with a recent survey by te Lintel Hekkert et al. (1990) reveals that more than 50% of our sources have OH maser emission at 1612 MHz. We argue that more than half of our stars are indeed in the bulge of our Galaxy. For an average distance of 8.06 kpc we then calculate the time averaged luminosity.

We have assumed that our sample is representative for a much larger sample of IRAS sources in the general direction of the bulge and with similar IRAS colours. We have subsequently used some of the characteristics of the observed sample (bolometric corrections at 12 μm, pulsation amplitudes) to translate the observed 12 μm flux density distribution of this larger sample into a distribution of mean luminosities. This distribution shows a strong peak between 5,000 and 5,500 L☉. It is not excluded that a small fraction have luminosities up to 10,000 L☉. It is very probable that there is a low luminosity tail of the distribution down to 1,000 L☉.

The periods and luminosities for the OH/IR stars in the bulge of our Galaxy fit very well into the period-luminosity relation found for Mira variables in the Baade windows. This confirms that the OH/IR stars in the galactic bulge are evolved from the Miras. From the luminosity function we conclude that the Miras and OH/IR stars in the galactic bulge have low mass progenitors (1.0–1.4 M☉) and are 7–15 Gyr old (assuming Z = 0.04).

Key words: galaxy: bulge of – stars: long period variables – stars: luminosities of – stars: OH/IR stars

1. Introduction

The all sky survey made by IRAS enables us to study the distribution of infrared point sources in our own Galaxy. From the position of our Sun (about 8.1 kpc from the galactic center) we see our Galaxy edge on. One of the most interesting results of IRAS was the picture of the disk and the bulge (Habing and Neugebauer, 1984), which was obtained by selecting sources with low 12 μm flux densities (F12 < 6 Jy) and red colours (F24/F12 roughly between 0.5 and 2). Immediately several questions arise:

(i) What is the nature of these IRAS sources?
(ii) What does their projected distribution learn about their spatial distribution?
(iii) What can be learned about kinematics of the populations?

This paper deals with the first question, with emphasis on the bulge sources. The last two questions, although very important, will not be investigated here. We refer to Habing et al. (1988) for some preliminary results.

Many of the IRAS sources in the disk were found to be associated with known Mira variables and OH/IR stars. Are the IRAS sources in the bulge similar to the Miras and OH/IR stars that we see in the disk? Several authors have tried to answer this question, each in their own way.

Feast (1986) suggested to study the nature of such IRAS sources in the “Baade windows” of low extinction, so they can directly be compared with the known Miras and M giants. He concluded that IRAS sources seen in the galactic bulge are in majority Mira or Mira-type variables.

Habing (1987) proposed that the reddest of these sources in the galactic bulge are objects similar to OH/IR stars. The existence of OH/IR stars in the central part of our Galaxy has been known already for a long time (Baud et al., 1975). At first this was confusing: OH/IR stars that were detected in the disk of our Galaxy, with distances derived from the phaselag method (Herman and Habing, 1985; Van Langevelde et al., 1990), seemed to indicate that OH/IR stars are rather luminous (L☉ > 104 L☉) and thus have rather massive progenitors. Does the galactic bulge consists of massive stars? Later it became clear that the luminous OH/IR stars found mainly in the disk belong to the tail of the luminosity distribution, which peaks around 5,000 L☉ (Habing, 1988).

In this paper we want to redo some of the earlier analyses of the IRAS bulge sources made by Habing (1986, 1987). First, because during the last 2 yr more accurate selection criteria have been developed to select evolved stars in different stages of their final evolution (e.g. Van der Veen and Habing, 1988; hereafter Paper I). Second, during the period 1985–1988 about 40 of the selected sources have been observed repeatedly between 2 and 13 μm at the European Southern Observatory (La Silla, Chile). Third, our knowledge about the evolution on and beyond the AGB and about their progenitors has considerably increased.

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during the last few years (e.g. Habing et al., 1988; Van der Veen, 1989; hereafter Paper II).

2. Source selection

How can we select stars from the IRAS Point Source Catalogue (IRAS PSC, 1985) that are part of the galactic bulge population? To answer this question we refer to Fig. 1, which was also shown in Paper I; it is the two-colour diagram of the 12, 25 and 60 μm IRAS flux densities. As discussed in Paper I, the regions I to V form an evolutionary sequence for oxygen-rich AGB stars, the regions VIa and VII contain carbon stars, and the regions VIb and VIII contain young stars, H II regions, and a few other types of sources. In the rest of this paper we will only use sources with good quality (Q = 3) flux densities at 12, 25 and 60 μm.

First, we discuss the distribution over the sky of the sources from the different regions of Fig. 1. We only consider the sky at |l| ≤ 90°, which we divide into 3 areas:

(i) the galactic plane with |b| ≤ 2°,
(ii) the intermediate latitude region with 2° < |b| ≤ 10°,
(iii) the high latitude region with |b| > 10°.

2.1. The galactic plane: |b| ≤ 2°

We divide this area into 4 longitude intervals: |l| ≤ 15°, 15° < |l| < 30°, 30° < |l| < 60°, and 60° < |l| < 90°. In total we find 2375 sources. For the 4 longitude intervals we find a source density of respectively 5.6, 6.3, 8.0 and 5.9 sources per square degree. That these numbers are about constant, suggest that we look at a nearby population. Independent of longitude about 85% of the sources have 12 μm flux densities less than 10 Jy. The majority (80%) of these relative faint sources are situated in region VIb (young stars) and VIII (H II regions), about 1/4 are situated in region IIIa and about 1/4 in region VII (carbon stars with circumstellar shells). Most of the bright (F12 > 10 Jy) sources are situated in region I (stars without circumstellar shells), region II (thin circumstellar shells), region IIIa (moderate circumstellar shells), and region VII (carbon stars with circumstellar shells). We conclude that for |b| > 10° we find a local population of evolved stars with thin to moderately thick circumstellar shells. Only 3% of all faint sources and 1% of all bright sources (F12 > 10 Jy) are stars with very thick circumstellar shells situated in region IIIb.

Only for |l| ≤ 15° and 2° < |b| ≤ 10° (the galactic bulge), an increase of the number density is found, mainly through sources with thick circumstellar shells (region IIIb). Do we find these

2.2. The intermediate latitude area: 2° < |b| ≤ 10°

This area is also divided into 4 longitude intervals as described before. In total we find 3454 sources. For |l| ≤ 15° we find a source density of 3.9 sources per square degree which is twice as high as for |l| > 15°, where we find respectively 2.2, 2.4 and 1.8 sources per square degree. Eighty percent of the sources at |l| ≤ 15° have 12 μm flux densities less than 10 Jy; for |l| > 15° this fraction is slightly smaller (70%). The fraction of faint sources from the regions VIb (young stars) and VIII (H II regions) is much smaller (1/3) than at |b| ≤ 2°. About half of the sources at |l| ≤ 15° is in regions IIIa and IIIb; at |l| > 15° this fraction is about 1/3. Especially the fraction of sources at |l| ≤ 15° and situated in region IIIb (very thick circumstellar shells) is at least a factor of 3 larger than in any other (l, b)-interval that we discuss here! Thus for |l| ≤ 15° we see a contribution from a relative distant population of stars with thick circumstellar shells.

2.3. The high latitude area: |b| > 10°

In total we find 2925 sources. The source density for the different longitude intervals is about the same: respectively 0.18, 0.15, 0.15 and 0.15 sources per square degree. Independent of longitude, 65% of the sources have 12 μm flux densities less than 10 Jy. About 20–40% of these faint sources are situated in the region VIb (young stars) and VIII (H II regions), about 1/5 are situated in region IIIa and about 1/4 in region VII (carbon stars with circumstellar shells). Most of the bright (F12 > 10 Jy) sources are situated in region I (stars without circumstellar shells), region II (thin circumstellar shells), region IIIa (moderate circumstellar shells), and region VII (carbon stars with circumstellar shells). We conclude that for |b| > 10° we find a local population of evolved stars with thin to moderately thick circumstellar shells. Only 3% of all faint sources and 1% of all bright sources (F12 > 10 Jy) are stars with very thick circumstellar shells situated in region IIIb.

Fig. 1. Regions in the IRAS two-colour diagram that separate different sort of evolved stars with circumstellar shells (Paper I). The "evolutionary track" from Miras to OH/IR stars is indicated by the dotted line.
bulge sources only in region IIIb? Using the infrared bolometric correction $BC_{12} = F_{\mu m} / (\nu F_{\nu})_{12\mu m}$ defined by Van der Veen and Breukers (1989), we find $L_\mu = 7.75 D^2 BC_{12} F_{12}$, where $L_\mu$ is in $L_\odot$, $D$ is in kpc, and $F_{12}$ is in Jy. Assuming a constant luminosity, $L_\mu = 5,000 L_\odot$, for an AGB star we find

$$D = \frac{25}{(BC_{12} F_{12})^{0.5}} \text{ kpc.}$$

As shown by Van der Veen and Breukers (1989), the average value of $BC_{12}$ is equal to 60, 10, 3, 3 and 5 for the sources in regions II, IIIa, IIIb, IV, and V respectively. Assuming a detection limit at 12 µm of 0.2 Jy, we can, in principle, detect an AGB star at 12 µm up to 7, 18, 30, 30 and 25 kpc. If we demand a good quality ($Q = 3$) flux density in all three wavelength bands, and if we have a detection limit of 0.2 Jy in all three bands, these distances reduce to 2, 7, 22, 30 and 25 kpc: i.e. we expect to detect sources that are part of the galactic bulge population ($D$ ~ 8 kpc) in regions IIIa, IIIb, IV, and V.

Are we complete in all these 4 regions? If we assume that the completeness limit of IRAS is at 1.5 Jy in all 3 wavelength bands (if we are out the plane) than we are complete up to 3, 8, 11 and 9 kpc for sources in the regions IIIa, IIIb, IV and V respectively. From this rough estimate we can expect to be complete for sources in region IV and almost complete for sources in region IIIb and V, but we are far from complete for sources in region IIIa.

On basis of the lifetime of stars in the regions IIIa, IIIb and IV (3 $10^5$ yr, 7 $10^3$ yr, and 300 yr respectively; Paper II) we conclude that the sources in region IIIb are the best suited to study the galactic bulge, although we might expect to find also some sources in the regions IIIa, IV, and V.

3. The IRAS sample of galactic bulge stars

3.1. Extent of the galactic bulge in the $(l, b)$-plane

We use the sources in region IIIb to find the extent of the galactic bulge in the $(l, b)$-plane. In Fig. 2a the number of sources integrated over all latitudes and as a function of galactic longitude for $|l| \leq 30^\circ$ is shown. The presence of the bulge is obvious; the slight asymmetry in this figure is probably not real. Assuming a symmetric distribution, we have averaged the numbers of the intervals $(-l, -l+\Delta l)$ and $(l, l+\Delta l)$ (Fig. 2b); the contribution of sources in the disk is indicated by the dashed line. We find that the bulge extends to $|l| \approx 15^\circ$.

Excluding the sources with $|l| > 15^\circ$, we have done the same to find the number of sources as a function of galactic latitude (Figs. 2c, d). The “dip” for $|b| < 2^\circ$ is not real, but is caused by
source confusion in the galactic plane. We find that the bulge extends to $|b| \approx 10^\circ$.

In the rest of this paper the area of the galactic bulge will be restricted to $|l| \leq 15^\circ$ and $|b| \leq 10^\circ$, but we will exclude the galactic plane ($|l| \leq 2^\circ$) in our analyses because there we expect confusion problems.

3.2. Subtraction of the contribution from the disk

To eliminate the contribution by sources in the disk we define two areas:

a) area A ($|l| \leq 15^\circ$, $2^\circ < |b| \leq 10^\circ$) contains a contribution from bulge + disk,

b) area B ($15^\circ < |l| \leq 30^\circ$, $2^\circ < |b| \leq 10^\circ$) contains only a contribution from the disk.

In Fig. 3a and b we show the numbers of sources in areas A and B arranged according to what region of the two-colour diagram they belong to. Assuming that the composition of the disk in area A is similar to the composition of the disk in area B we can separate statistically the disk and the bulge by subtracting the number of sources in area B from the number of sources in area A: the result is shown in Fig. 3c; the errorbar is defined as $\sqrt{N_1 + N_2}$, where $N_1$ is the number of sources in a certain bin in Fig. 3a, and $N_2$ is the number of sources in the corresponding bin in Fig. 3b. Figure 3c shows that there is a significant "bulge contribution" from:

(i) region IIIa: stars with optically thin shells – e.g. Mira variables,

(ii) region IIIb: stars with optically thick shells – e.g. OH/IR stars,

(iii) region IV: stars with extreme optically thick shells,

(iv) region V: planetary nebulae,

(v) region VIb: probably young stars and proto-stars.

The first four groups are probably all in the galactic bulge, but the stars in group (v) are probably foreground objects; we suggest that they belong to the Ophiuchus molecular cloud, which contributes only to the disk seen in area A and not to the disk seen in area B.

These results show that, a simple subtraction provides us with the size of the bulge sample in each region of the IRAS two-colour diagram (Fig. 3c) and their 12 $\mu$m flux density distribution. The most important contribution is from stars with IRAS colours similar to Miras, OH/IR stars and planetary nebulae, with only a small (10%) contamination of a local population of young stars. These young stars can be excluded from the sample by excluding the sources of region VIb. This, however, can only be done if a reliable 60 $\mu$m flux is present (see Fig. 1). The selection criteria used by Habing (1986) did not take the 60 $\mu$m flux density into account, and hence his sample is contaminated by a small fraction of young, local, stars.

From Fig. 3c we get an idea about the completeness of our sample by assuming that all sources are part of the galactic bulge. From Fig. 3c we find $N$(IIIa):$N$(IIIb):$N$(IV) = 10:9:1. We can compare this with a prediction on basis of the relative lifetime $t$(IIIa):$t$(IIIb):$t$(IV) = 1000:24:1 (Paper II). Assuming that we are complete for sources in region IV, this implies that we are 40% complete for sources in region IIIb, but only 1% complete for sources in region IIIa. This conclusion is in agreement with the discussion earlier in Sect. 2 on the limiting distance for each region.

3.3. The 12 $\mu$m flux density distribution of galactic bulge stars

The 12 $\mu$m flux density distribution for all sources in area A and B (Sect. 3.2) are shown in Fig. 4a and b respectively. In Fig. 4a the

Fig. 3a–c. Number of sources situated in the different regions of the IRAS two-colour diagram (Fig. 1)
numbers increase systematically by a factor of 4 towards lower 12 μm flux densities; in Fig. 4b, however, this increase is only a factor of 2. Subtracting both distributions yields the 12 μm flux density distribution for the galactic bulge sources as shown in Fig. 4c; error-bars are indicated and defined in the same way as in Sect. 3.2. The distribution peaks between 3 and 4 Jy. This flux distribution cannot directly be translated into a luminosity distribution, because the bolometric correction is not the same for all sources, but ranges from about 3 to 10. Moreover, there is also a contribution from the sources in region VIb of Fig. 1 (young stars). In order to separate the contribution of different type of sources we repeated this analysis for the different regions of Fig. 1 that contribute to the 12 μm flux density distribution. The results of the subtraction of area A and B (Sect. 3.2) are shown in Fig. 5a–e.

a) In Fig. 5a we show the 12 μm flux density distribution for the sources of region IIIa. With the chosen bin size of 1 Jy, there is only a significant (>3σ) contribution from the 3–4 Jy, 6–7 Jy and the 8–9 Jy bin. The overall distribution is rather flat, reaching a maximum between 6 and 9 Jy. This is probably caused by a small increase in the number of disk sources in the line of sight towards smaller longitudes.

b) In Fig. 5b we show that the 12 μm flux density distribution for the sources of region IIIb. With the chosen bin size of 1 Jy there is a significant contribution from all bins between 2 and 7 Jy. The overall distribution is strongly peaked between 3 and 7 Jy with a flat tail going to larger flux densities. We attribute this tail to a small increase in the number of disk sources in the line of sight towards smaller longitudes. An important question remains: is the decrease of sources with fluxes below 4 Jy real or caused by the detection limit of IRAS? We will try to answer this important question later in this paper.

c) In Fig. 5c we show the 12 μm flux density distribution for the sources found in region IV of Fig. 1. These sources contribute significantly to the 3–4 Jy bin only. The overall distribution suggests a small peak between 3 and 4 Jy and a flat distribution between 4 and 10 Jy, which we attribute to a small increase in the source density towards smaller longitudes. Later in the paper we will discuss the significance of the small peak between 3 and 4 Jy.

d) In Fig. 5d we show the 12 μm flux density distribution for the sources of region V. The sources contribute significantly to the bins below 3 Jy. Notice that we find no sources for $F_{12} > 4$ Jy!!!

e) In Fig. 5e we show the 12 μm flux density distribution for sources of region VIb. These sources contribute significantly to the 2–3 Jy bin only. The overall distribution shows a relative strong increase between 1 and 3 Jy followed by a strong decrease and a long tail that extends to 10 Jy. As mentioned before these sources have colours similar to young stars and proto-stars and we attribute them to young stars in the Ophiuchus molecular cloud region.

The most promising sources for further study are those of region IIIb. From a comparison of Fig. 4c and Fig. 5b we see that these sources dominate the 12 μm flux density distribution; the sources from the other regions only broaden this distribution. Before we try to interpret these 12 μm flux density distributions, we first discuss the characteristics of sources in region IIIb using additional observations in the near infrared.
Fig. 5a–e. 12 μm flux density distribution for IRAS sources situated in the regions IIIa, IIIb, IV, V, and VIb of the IRAS two-colour diagram (Fig. 1).

4. The characteristics of evolved AGB stars in the galactic bulge

4.1. Near infrared observations

What are the characteristics of the evolved AGB stars in region IIIb? To answer this question we started an observing program at the European Southern Observatory (ESO) using the 2.2 m and 3.6 m telescope. We observed 37 sources situated in region IIIb of Fig. 1 and with $|l| \leq 10^\circ$ and $2^\circ < |b| \leq 10^\circ$; we have left out the sources with $10^\circ < |l| < 15^\circ$, because the relative numbers of bulge sources with respect to disk sources goes down very rapidly with increasing longitude (Fig. 2). The sample of 37 sources is chosen to be equally distributed in the $(l, b)$-plane and contains about 20% of all sources that fulfill the criteria listed above.

The observations were obtained during 4 observing runs each separated by about one year; exact dates are given in Table 1. The photometry was carried out with observatory InSb (1–5 μm) and bolometer (2–13 μm) instruments. Observations were carried out in 6 wavelength bands with the following central wavelengths and band widths: K (2.18, 0.40 μm), L (3.76, 0.70 μm).
M(4.69, 0.50 μm), N1(8.38, 0.96 μm), N2(9.69, 1.50 μm) and N3(12.85, 1.38 μm). In the first two runs we used the bolometer to cover the whole wavelength range. During the last two runs we continuously switched between the InSb detector (which has a higher sensitivity in the K, L and M band than the bolometer) and the bolometer (which was used for the N1, N2 and N3 band only).

The positions of the objects were obtained from the IRAS PSC (1985). In general we searched for the sources in the L(3.76 μm) band, as suggested by Jones et al. (1981) for sources with expected K − L magnitudes significantly larger than one, to avoid confusion with field stars. Considerable care has been taken when observing sources in crowded regions, to ensure that no spurious sources were included in the beam. The infrared position were determined by centering the sources in both δ and δ with steps of 0.5″; the positions were calibrated using bright nearby SAO stars with known 1950.0-positions. Most of the sources (80%) were found within 7″ from the IRAS position. A list of observed infrared positions and their difference with IRAS position is given in Table 2. During the observations sky subtraction was accomplished by a combination of chopping and beam switching over an angle of respectively 22° and 15° in α when a 10° or 8° diaphragm was used. The integration time for each star ranged from 80 to 200 s per filter depending on the brightness of the source in that band.

During the night several standard stars at different airmasses were measured at regular time intervals. The absolute calibration of the measurements was accomplished using the table of infrared standard stars as published by Koornneef (1983) and the ESO table of bolometer standard stars which was obtained from different sources (e.g. Thomas et al., 1973). The observed magnitudes are listed in Table 3. Table 4 lists the (l, b)-position, the 12 μm flux density, the [12]−[25] and the [25]−[60] colours defined as

\[C_{12} = 2.5 \log(F_{12} / F_{25})\]

and

\[C_{25} = 2.5 \log(F_{25} / F_{60})\]

and the IRAS variability index, VAR. The table also gives OH(1612 MHz) data for all sources that have been detected in a recent OH-survey by te Lintel Hekkert et al. (1990): kinematic velocities \(v_r\), separation between the two maser peaks \(\Delta l\), and the flux of the low \(L(V)\) and high \(H(V)\) velocity peak. About half the sources coincide with an OH(1612 MHz) maser characteristic for OH/IR stars; for 25% of the sources no maser was detected and another 25% have not yet been looked at.
4.2. The energy distribution and the 9.7 μm feature

The energy distribution ($\lambda F_{\lambda}$) of the observed sources was determined by using the calibration constants for a 0.0 mag star as given in Table 5. We did not correct the fluxes for interstellar extinction. This may mean that the total fluxes found from these uncorrected energy distributions are a lower limit to the bolometric flux of the observed star; the difference however is not larger than 10%.

Although some of the sources have not been detected in the OH(1612 MHz) line (Table 4), all sources show an energy distribution typical for AGB stars with moderate to thick circumstellar shells, similar to those we know already for a long time in the galactic disk (e.g. Herman et al., 1984). As an example, in Fig. 6a we show the energy distribution of IRAS 17030-3053; the source was observed three times with a time difference between successive observations of about one year (full line, dashed line and dotted line). The IRAS fluxes from the IRAS PSC (1985) are plotted three times, each time shifted in intensity to fit the ground based 12.9 μm flux.

In 35 out of 37 sources we find the 9.7 μm silicate feature (SiO on grains) in absorption (see also Fig. 6a), which is so typical for optically thick circumstellar shells, and in only two (IRAS 16574-2733 and IRAS 18279-2707, which is shown in Fig. 6b) this feature is in emission, indicative of an optically thin shell. Both the 9.7 μm emission and absorption feature prove that the stars are oxygen-rich. The strength of this feature differs from one source to the other: a correlation between the depth of this feature, defined as $A_{9.7}/F_{9.7} = -2.5 \log(F_{9.7}/F_{\text{cont}})$ and the [12]–[25] colour is shown in Fig. 7, where $F_{\text{cont}}$ is determined as

$$F_{\text{cont}} = 0.5(F_{8.7\mu m} + F_{12.9\mu m}).$$

This correlation was also found for OH/IR stars in the disk of our Galaxy (Herman et al., 1986) and is also predicted by theoretical models (Bedijn, 1987; Schulte and Thielen, 1989). There is no obvious systematic difference between sources with $F_{12} > 7$ Jy (mainly situated in the disk; see Fig. 5b) indicated by crosses and sources with $F_{12} < 7$ Jy (mainly situated in the bulge; see Fig. 5b) indicated by black dots. This indicates that the feature mainly has a circumstellar origin and not an interstellar one, as one might suspect because of the long distance towards these objects. A best fit to the observed points yields

$$F_{12} > 7 \text{ Jy: } A_{9.7} = 0.2(2) + 1.3(3)[(12)–[25]],$$

$$F_{12} \leq 7 \text{ Jy: } A_{9.7} = -0.2(2) + 1.5(3)[(12)–[25]],$$

indicated respectively by the dashed and dotted line in Fig. 7.
Taking into account the errors, the results are not significantly different. However, we want to point out that $A_{9.7}$ seems smaller for sources with $F_{12} \leq 7$ Jy than for sources with $F_{12} > 7$ Jy, which is the opposite from what could be expected because the fainter sources are at a larger distance and thus more affected by interstellar absorption at 9.7 μm.

The results can be compared with the results from Herman et al. (1986), who found $A_{9.7} = -0.5 + 2.6 ([12]−[25])$ for OH/IR stars in the disk of our Galaxy (full line in Fig. 7). In the above analysis we did not correct for the fact that low resolution spectra ($\lambda/\Delta \lambda \sim 10$) are used to measure the 9.7 μm absorption; in the original equation given by Herman et al. (1987) they assumed a constant correction of +0.32 mag due to foreground extinction.

As is clearly shown in Fig. 6a, the sources show a large variability: for IRAS 17030-3053 the whole spectrum shifts over a factor of 3 within one year. Similar changes are also observed in other sources. That the sources are variable was already clear from the large IRAS variability index, VAR, for the majority of the sources (Table 4). Such large shifts of the spectrum in one year suggests that these sources must have pulsation periods of at least 300 to 600 days. The same was concluded by Harmon and Gilmore (1987) on basis of simulated distributions of $N(VAR)$ for different period ranges.

4.3. Bolometric fluxes, bolometric corrections, periods, and amplitudes

Integrated fluxes were calculated by connecting all observed $F_{\lambda}$ points by a straight line and integrating under the curve, which is accurate up to 10%. To find the integrated fluxes at the different times of observation, we have proceeded in the following way. For all sources we obtained the 12, 25 and 60 μm flux densities from the IRAS Working Survey Data Base (IRAS WSDB, 1985), which gives values for each of the 2 to 5 times that the source was observed by IRAS. First we used the IRAS PSC flux densities as an average for each 12–60 μm spectrum and shifted this spectrum with respect to the 2–13 μm spectrum measured from the ground. Second, we used the average of the 2–13 μm spectrum (from the ground based observations) and shifted this spectrum with respect to each 12–60 μm spectrum (from the IRAS WSDB). This procedure yields 3 to 7 values for the integrated flux in the time interval from February 1983 to July 1988. Examining the 2–13 μm spectrum we find that its shape does not change significantly with pulsation period (Fig. 6a); the same holds for the 12–60 μm spectrum as found from the IRAS WSDB. This confirms the result found by Forrest et al. (1978) that the shape of the spectrum for optically thick shells varies little with pulsation period. For the 35 sources with spectra similar to those shown in Fig. 6a, the integrated flux between 2 and 60 μm equals the bolometric flux of the central star; for the 2 sources with spectra similar to the one shown in Fig. 6b, the integrated flux between 2 and 60 μm is a lower limit to the bolometric flux, because a significant fraction of the flux is radiated at wavelengths shorter than 2 μm.
Fig. 8. $M_{bol}$ as a function of time (JD-2400000) for IRAS 17030-3053. Open circles are scaled to the $12 \mu m$ flux density measured by IRAS; black dots are scaled to the $12 \mu m$ flux density obtained from ground based observations. A best fit to Eq. (3) is indicated by the full line.

Table 6a. Luminosities, amplitudes, and periods of disk sources

| IRAS   | $\phi$ | $P_{Jy}$ | $<M_{bol}>$ | $\Delta M_{bol}$ | $<L_{bol}>$ | $P_{bol}$ | $T_{bol}$ | JD      | N       |
|--------|--------|----------|-------------|------------------|-------------|-----------|-----------|--------|
| 19714-3140 | 0.29   | 11.1     | -5.8        | 1.0              | 21,000      | 600       | 46070     | 4+1    |
| 17118-2925 | -0.17  | 7.8      | -5.3        | 0.8              | 12,000      | 720       | 45790     | 3+2    |
| 17239-2941 | 0.08   | 13.2     | -6.5        | 0.9              | 36,000      | 940       | 45670     | 3+1    |
| 17338-2140 | 0.12   | 3.5      | -5.3        | 0.7              | 12,000      | 720       | 45630     | 3+1    |
| 17367-3631 | 0.02   | 8.8      | -6.4        | 0.9              | 36,000      | 940       | 45640     | 3+2    |
| 17375-3502 | -0.29  | 125.0    | -8.5        | 0.7              | 210,000     | 1,100     | 45980     | 4+1    |
| 17384-2534 | 0.09   | 10.7     | -5.6        | 0.7              | 15,000      | 750       | 45780     | 3+1    |
| 18421-2720 | -0.21  | 14.2     | -6.0        | 0.7              | 21,000      | 610       | 46160     | 3+1    |
| 18707-2614 | -0.38  | 10.1     | -5.2        | 0.5              | 24,000      | 1,000     | 46300     | 3+2    |
| 19514-2003 | -0.28  | 8.1      | -5.4        | 0.5              | 12,000      | 520       | 45830     | 3+1    |
| 18624-2720 | -0.47  | 9.0      | -5.3        | 0.7              | 12,000      | 750       | 45680     | 3+2    |
| 18803-3003 | 0.49   | 11.4     | -5.2        | 0.8              | 11,000      | 710       | 45605     | 3+1    |
| 18931-2934 | 0.26   | 8.6      | -5.8        | 0.7              | 15,000      | 870       | 46320     | 3+2    |

In Fig. 8 we show $M_{bol}$ as a function of time (Julian date) for IRAS 17030-3053; bolometric magnitudes found from shifting the 2–13 $\mu$m spectrum (ground based observations) with respect to the 12–60 $\mu$m spectrum (IRAS observations) are indicated by open circles, and bolometric magnitudes found from shifting the 12–60 $\mu$m spectrum with respect to the 12–13 $\mu$m spectrum are indicated by black dots. We tried to fit a periodic function to the observed bolometric magnitudes of the form

$$M_{bol}(t) = \langle M_{bol}\rangle + \Delta M_{bol} \sin \left(\frac{2\pi t}{P} + \phi\right),$$

where we have searched for periods between 100 and 2000 days.

It should be mentioned here that actual light curves of OH/IR stars are often asymmetric and not necessarily regular (e.g., Le Bertre, 1988). However, because most of our light curves consists of 4–7 points only, it is not possible to fit more sophisticated functions that take into account such asymmetries. Therefore, especially the phase determinations described below should be considered as a rough estimate only.

No solution could be found for IRAS 17088-2700 and IRAS 17276-2846 because for both sources only 3 measurements of $M_{bol}$ are present. For 29 sources we have found a unique solution and for six they are not unique. More observations (to be made in July 1989) might cure this situation. The results are presented in Table 6. There we give the $12 \mu m$ flux density from the IRAS PSC, the mean bolometric magnitude $\langle M_{bol}\rangle$, the amplitude $\Delta M_{bol}$, the period $P$ (in days), the time of minimum $T_0$ (in JD-240000), and the number of individual estimates of $M_{bol}$ (number of estimates from IRAS + number of estimates from ground based observations).

The quantity of physical interest is the mean luminosity, $\langle L_{bol}\rangle$, which is also given in Table 6 and can be found from the following approximate equation

$$\langle L_{bol}\rangle = \frac{10^{0.4(4.72 - \langle M_{bol}\rangle)}(10^{0.32M_{bol}+0.3})}{2}$$

which is accurate within 3% for $\Delta M_{bol} < 3$ mag.

We distinguish 2 classes of sources on the basis of their mean luminosity for an assumed distance of 8.06 kpc:

a) $\langle L_{bol}\rangle > 10^4 L_\odot$, and the source is listed in Table 6a,

b) $\langle L_{bol}\rangle \leq 10^4 L_\odot$, and the source is listed in Table 6b.
Table 7. OH (1612 MHz) characteristics for sources in Tables 6a and 6b

<table>
<thead>
<tr>
<th>Table 6a</th>
<th>Table 6b</th>
</tr>
</thead>
<tbody>
<tr>
<td>population</td>
<td>disk</td>
</tr>
<tr>
<td>detected</td>
<td>64%</td>
</tr>
<tr>
<td>not detected</td>
<td>36%</td>
</tr>
<tr>
<td>not observed</td>
<td>0%</td>
</tr>
<tr>
<td>$&lt; S_{141} &gt;$ (Jy)</td>
<td>1.1</td>
</tr>
<tr>
<td>$&lt; v_x &gt;$ (km/s)</td>
<td>-9</td>
</tr>
<tr>
<td>$\sigma(v)$ km/s</td>
<td>54</td>
</tr>
<tr>
<td>$v_x$ (km/s)</td>
<td>14.8 ± 0.8</td>
</tr>
</tbody>
</table>

Fig. 9. 12 µm flux density from the IRAS PSC as a function of the phase ($\phi$) at the moment that the source was measured by IRAS; $|\phi|=0$ indicates minimum light

All sources with $F_{12}>7$ Jy according to the IRAS PSC have luminosities above $10^8 L_\odot$, if a distance of 8.06 kpc is assumed. In Sect. 3.3 we have indicated that these sources are probably situated in the disk at a distance less than 8.06 kpc. All sources with $F_{12}\leq7$ Jy according to the IRAS PSC have luminosities less than $10^8 L_\odot$, except for IRAS 17338-2140. According to Fig. 5b, the majority of these sources are part of the bulge.

An additional test to find out whether this separation indeed creates physically different samples can be done using the OH(1612 MHz) data given in Table 4, although the size of the sample is small (about 10 objects in each class). In Table 7 we have listed the OH(1612 MHz) characteristics of the sources with $<L_x>=10^8 L_\odot$ (Table 6a) and with $<L_x><10^8 L_\odot$ (Table 6b). The detection rate in OH is slightly larger for the sources of Table 6a. The average kinetic velocity, $<v_x>$, and, more importantly, the velocity dispersion, $\sigma(v)$, is larger for the sources of Table 6b, which are thought to be in the galactic bulge. We also find systematic smaller OH-fluxes and expansion velocities for the bulge sources. The latter is expected because the expansion velocity tends to increase with bolometric luminosity as was found for a large sample of OH/IR stars (Jones, et al., 1983).

In column 2 of Table 6 we have listed the phase, $\phi(-0.5<\phi<0.5)$, of the light curve that corresponds with the moment that the IRAS measurements were made. Phase $\phi=0$ corresponds with minimum light and was calculated from the period, $P$, and time of minimum light, $t_0$, as listed in column 7 and 8 of Table 6. If $\phi<0$ the source was decreasing in luminosity when observed by IRAS, if $\phi>0$ the source was increasing in luminosity. IRAS 17338-2140 was measured at minimum light ($|\phi|=0.12$) and therefore has a 12 µm flux density (in the IRAS PSC) of 3.5Jy, whereas the mean luminosity is larger than $10^8 L_\odot$.

In Fig. 9 we have plotted $F_{12}$ (from the IRAS PSC) versus $|\phi|-0.5<|\phi|<0.5$. This figure was shown earlier by Van der Veen (1988) when we did not have the data from our last ESO run (July 1988). With the available observations at that time it was shown that the lower left part of Fig. 9 ($F_{12}<4.5$ Jy, $|\phi|>0.3$) contained only one source. Using the data of the last ESO run (July 1988) we are now able to find more reliable values for $|\phi|$ and also 5 sources for which no value of $|\phi|$ was available at that time are now added. Now the right side of Fig. 9 is filled up. Although we have argued before that the values of $\phi$ are rough estimates only we do not believe that this account completely for the observed scatter in Fig. 9. Hence we arrive to the conclusion that there might still be a significant amount of sources with $F_{12}<0.8$ Jy (the faintest sources found in the IRAS PSC) that are not in the IRAS PSC because they were at the minimum of there light when measured by IRAS.

Of all sources in Table 6a with a unique solution, none has a period less than 500 days, seven (70%) have a period between 500 and 1,000 days, and three (20%) have a period longer than 1,000 days; for the sources in Table 6b these numbers are 0 (0%), 10 (53%) and 9 (47%) respectively. Our sample is too small to add any significance to the fact that more long periods ($P>1,000$ days) are found in Table 6b (bulge stars) than in Table 6a (disk stars). The main conclusion, however, is that all sources have periods larger than 500 days, in agreement with periods found for OH/IR stars in other studies (from infrared light curves: Engels, 1983; from OH (1612 MHz) light curves: Herman et al., 1986).

All sources for which a unique solution was found have amplitudes between 0.4 and 1.1 mag. For sources in Table 6a there is a peak in the distribution between 0.7 and 0.9 mag; sources in Table 6b do not show such a peak and seem to have a flat distribution between 0.4 and 1.1 mag. We find mean amplitudes of 0.74±0.15 mag and 0.7±0.3 mag for the sources in Tables 6a and b respectively.

It was shown by Herman et al. (1986) for 2 sources with a good period coverage in the infrared and in the OH (1612 MHz) line, that the amplitudes found from the OH lines are almost identical to those found from the infrared spectrum. From his sample of OH/IR stars he found amplitudes between 0.6 and 1.4 mag with an average of 1.1±0.4 mag.

5. Luminosity function, period-luminosity relation, initial masses, and ages

5.1. The luminosity function of galactic bulge stars

In the rest of this paper we distinguish between the luminosity function (defined as the distribution of mean luminosities) and the observed luminosity distribution. In Sect. 3.3 we have stated that the 12 µm flux density distribution for galactic bulge sources of
region IIIb strongly peaks between 3 and 7 Jy (Fig. 5b), and only a very small fraction have flux densities larger than 7 Jy. Because for these sources the bolometric correction is approximately constant ($BC_{12} = 2.8 \pm 0.2$), the 12 $\mu$m flux density distribution can directly be translated into a luminosity distribution using

$$L_\star = 1,400 \left( \frac{F_{12}}{\text{Jy}} \right) \left( \frac{D}{8.06 \text{ kpc}} \right)^2 L_\odot. \quad (6)$$

The luminosity distribution found in this way is not the same as the luminosity function, because the sources are variable. From a combination of Eqs. (4) and (5) we find

$$L_\star(\phi) = 2 \left( \frac{L_\star}{L_\odot} \right) \frac{10^{-0.4 M_{\text{bol}} \cos \phi}}{10^{0.3 M_{\text{bol}} + 10^{-0.3 M_{\text{bol}}} L_\odot}}. \quad (7)$$

In combination with Eq. (6) this equation yields

$$F_{12}(\phi) = \frac{10^{-0.4 M_{\text{bol}} \cos \phi}}{700 \left( \frac{D}{8.06 \text{ kpc}} \right)^2 10^{0.3 M_{\text{bol}} + 10^{-0.3 M_{\text{bol}}} \text{Jy}}. \quad (8)$$

If a distribution over the mean luminosity $\langle L_\star \rangle$ (luminosity function), the amplitude, $M_{\text{bol}}$, and the distance, $D$, are known, Eq. (13) can be used to find the $F_{12}$-distribution. We will assume the following simplified distribution functions:

$$f_1(D) = \text{const.}, \quad \text{for } 7.06 \text{ kpc} \leq D \leq 9.06 \text{ kpc}$$

$$f_2(D) = 0, \quad \text{for } D < 7.06 \text{ kpc} \text{ or } D > 9.06 \text{ kpc}$$

$$f_3(M_{\text{bol}}) = \text{const.}, \quad \text{for } 0.4 \leq M_{\text{bol}} \leq 1.1 \quad (\text{Sect. 4.3})$$

$$f_4(M_{\text{bol}}) = 0, \quad \text{for } M_{\text{bol}} < 0.4 \text{ or } M_{\text{bol}} > 1.1$$

$$f_5(\phi) = \text{const.}, \quad \text{for } 0 \leq \phi \leq 2\pi.$$

The depth of the bulge is based on a distance to the galactic center of 8.06 kpc and Fig. 2, where the number of sources decreases strongly for $|l| > 10$.

We have tried to find luminosity functions that reproduce Fig. 5b between 4 and 8 Jy. For $F_{12} < 4$ Jy we expect deviations from the distribution because of the incompleteness of the IRAS PSC. This limit is higher than assumed before (1.5 Jy) because the sources are highly variable. In Sect. 3.3 we have already stated that the tail for $F_{12} > 10$ Jy is due to an increasing source density in the disk towards smaller longitudes.

First we have tried to fit the distribution between 4 and 8 Jy assuming a luminosity function which is as narrow as possible. We find that the observed $F_{12}$-distribution can be explained rather well if all stars have luminosities between 5,000 $L_\odot$ and 5,500 $L_\odot$ (dashed line in Fig. 5b). A luminosity distribution between 4,500 $L_\odot$ and 5,000 $L_\odot$ yields a $F_{12}$-distribution systematically below the observed distribution and for a luminosity distribution between 5,500 $L_\odot$ and 6,000 $L_\odot$ the opposite is true. The dashed line in Fig. 5b shows that we miss about 35% of the sources with $1 < F_{12} < 3$ Jy, but that the sources with $F_{12} < 1$ Jy are over represented. This indicates that there must be a significant contribution of luminosities lower than 5,000 $L_\odot$. We will come back to this later in this section. The dashed line predicts 216 galactic bulge sources in region IIIb, about 30% more than observed.

Second we have tried to find an upper limit to the number of sources with luminosities above 5,500 $L_\odot$. We find several luminosity functions that reproduce the 12 $\mu$m flux density distribution between 4 and 8 Jy; the total number of sources that corresponds with all these distributions is about 220. The different possible luminosity functions longward of 5,500 $L_\odot$ are:

(i) A maximum of 25% have mean luminosities between 5,500 $L_\odot$ and 6,000 $L_\odot$.

(ii) A maximum of 20% have mean luminosities between 5,500 $L_\odot$ and 7,000 $L_\odot$, of which 10% have mean luminosities around 6,000 $L_\odot$, 5% have mean luminosities around 6,500 $L_\odot$, and another 5% have mean luminosities around 7,000 $L_\odot$.

(iii) A maximum of 15% have mean luminosities between 5,500 $L_\odot$ and 8,500 $L_\odot$. The sources have to be about equally distributed between 5,500 and 8,500 $L_\odot$ so that only 6% have mean luminosities between 7,500 and 8,500 $L_\odot$.

(iv) A maximum of 10% have mean luminosities between 5,500 and 10,000 $L_\odot$. The sources have to be equally distributed between 5,500 and 10,000 $L_\odot$, which means that only 3% sources can have mean luminosities between 8,500 and 10,000 $L_\odot$.

On the basis of Fig. 5b we cannot exclude the possibility that there are sources in the galactic bulge with $< L_\star > > 10,000 L_\odot$. We can, however, conclude that there are less than 2% of them, assuming that all sources with $F_{12} > 10$ Jy are disk sources and show up because of a small increase in their number densities with decreasing longitude.

A similar analysis to derive the fraction of mean luminosities less than 5,500 $L_\odot$ is difficult, because it would be mainly based on the numbers for $F_{12} < 4$ Jy, where our sample is incomplete. On the other hand at most 20% of all sources can have mean luminosities less than 5,000 $L_\odot$, because otherwise this will affect the relative numbers for $F_{12} > 4$ Jy. We have already mentioned that lower luminosity sources are needed to predict more sources in the flux interval $F_{12} < 1$ Jy. Also from Fig. 9 we concluded that there are probably a significant number of IRAS sources with $F_{12} < 1$ Jy that are not in the IRAS PSC. Increasing the number of sources in the intervals for $F_{12} < 1$ Jy can for example be done using a luminosity distribution where 80% of the sources have luminosities between 5,000 $L_\odot$ and 5,500 $L_\odot$, and where the rest is equally distributed down to 1,000 $L_\odot$. However, other distributions are also possible.

Summarizing our results on basis of Fig. 5b we have found that the majority of the sources must have luminosities between 5,000 $L_\odot$ and 5,500 $L_\odot$. A maximum of 20% of the sources can have luminosities down to 1,000 $L_\odot$. An extended tail (containing 10–20% of all sources) in the luminosity function towards high luminosities is possible, but their number have to be small, e.g. not more than 2% can have luminosities larger than 10,000 $L_\odot$.

These results are different from what was found by Jones and Hyland (1986). They observed 15 out of the 33 OH/IR within 30' of the galactic center from the OH (1612 MHz)-sample of Winneberg et al. (1985) and found that the luminosities range from a few times $10^{3}$ $L_\odot$ up to the AGB limit of 6 $10^{4}$ $L_\odot$. There are four reasons why their luminosities are expected to be systematically larger than we have found for our sample.

(i) Jones and Hyland (1986) used a distance of 8.7 kpc (Graham, 1979) where we have used a distance of 8.06 kpc (Wesselink, 1987).

(ii) The $L'(3.8 \mu m)$ magnitudes of Jones and Hyland are corrected for an interstellar extinction of 0.9 mag based on Jones and Hyland (1980) and Rieke and Lebofsky (1985). We did not do these corrections because our sources are at least 2* out of the galactic plane and the corrections are small and uncertain.

(iii) Most important, Jones and Hyland neglected the variability of the sources which was claimed to be a few tenths on average. Our observations of galactic bulge sources, however, shows that the $L$-magnitudes can change by up to 2 magnitudes.
during a pulsation cycle. We think that the range in luminosities up to the AGB-limit of 60,000 $L_\odot$ as found by Jones and Hyland is largely caused by the variability of the sources. The fact that no sources were found to exceed the AGB-limit already points in the direction of lower mean luminosities.

(iv) The sources in the galactic center might be expected to have systematically larger luminosities than in the galactic bulge. They might have probably formed more recently and are thus more massive and more luminous.

5.2. P-L relation for OH/IR stars and Miras in the galactic bulge

Period-luminosity (P-L) relations have been used to study and compare the properties of long period variables – especially Mira variables – in the LMC (e.g. Feast, 1984; Glass et al., 1987; Wood, preprint), in the galactic globular clusters (e.g. Feast, 1984; Menzies and Whitelock, 1985) and in the galactic bulge (e.g. Feast, 1986). These relations are of the form $M_{bol} = A_0 - A_1 \log P$, where the slope, $A_1$, is best determined for Miras in the LMC: $A_1 = -3.3 \pm 0.2$ (Glass et al., 1987). For the galactic globular clusters or for the galactic bulge similar values for $A_1$ are found (Feast, 1986).

In Paper II, a relation is given between pulsation period, $P$, luminosity, $L_*$, and the present-day envelope mass, $M_e$, for a sample of OH/IR stars in the disk of our galaxy

$$P = 3.7 \left( \frac{L_*}{M_e} \right)^{0.5}$$

(9)

where $P$ is in days, $L_*$ is in $L_\odot$, and $M_e$ is in $M_\odot$. During the evolution at the top of the AGB, the envelope mass decreases because of hydrogen burning at the base and mass loss in the outer parts. Hydrogen burning adds new material (helium) to the core at a rate of $10^{-7} M_\odot/yr$; the increase in core mass manifests itself as a linear increase in luminosity (Paczynski relation). Mass loss occurs at a much higher rate than hydrogen burning: from $10^{-5} M_\odot/yr$ for Miras to $10^{-4} M_\odot/yr$ for more evolved stars such as OH/IR stars. There are thus two time scales involved: one for the increase of luminosities ($\sim 10^6$ yr) and one for the mass loss rate ($\sim M_e/M$). The interplay between these two timescales determines the slope of the P-L relation. Such relations for stars with different initial masses are given in Paper II; the calculations are based on Eq. (9) and a mass loss rate that increases very strongly with time. For all initial masses these P-L relations have the same shape when $M_{bol}$ is plotted versus log $P$: for $P \lesssim 300$ days the slope, $A_1$, equals $-3.5$, for $300 < P \lesssim 500$ days the slope decreases and for $P > 500$ days, $M_{bol}$ is constant. For larger initial masses the curves are shifted towards larger luminosities. Luminosity increase as a function of period is only expected when stars have relative low mass loss rates ($10^{-6} M_\odot/yr$); a constant luminosity as a function of period is expected when the stars are in a phase of relative high mass loss ($10^{-5} - 10^{-4} M_\odot/yr$).

In Fig. 10, a sample of galactic bulge Miras (observed in the Baade windows) with known periods and bolometric magnitudes is indicated by crosses. The data are taken from Fig. 2 of Feast (1986) where we have used a relation given by Feast (1984) to convert the K-magn versus P diagram (Fig. 2 in Feast, 1986) into an $m_{bol}$ versus $P$ diagram. A distance modulus ($m-M)_0 = 14.53$, which corresponds with a distance of 8.06 kpc (Wesselink, 1987), was used to transform $m_{bol}$ in $M_{bol}$. The black dots in Fig. 10 represent the results for the sample of stars listed in Table 6b. These objects in our sample are an extrapolation of the galactic bulge Miras towards longer periods, but not towards larger luminosities. This is expected when both classes of objects have the same initial masses. P-L relations similar to those given in Paper II are indicated by the dashed lines: a star with a given initial mass will follow such a curve during its AGB evolution from Mira variable to OH/IR star. The different curves correspond with maximum AGB luminosities of 10,000 $L_\odot$ (curve a), 7,000 $L_\odot$ (curve b), 5,500 $L_\odot$ (curve c), and 4,000 $L_\odot$ (curve d).

The spread in $M_{bol}$ is partly due to the depth of the galactic bulge and partly due to a spread in intrinsic luminosities and uncertainties in the determination of the mean bolometric magnitudes. Again we see that a significant fraction have low luminosities ($L_e < 4,000 L_\odot$, $M_{bol} < -4.3$). About half of the observed sources in Fig. 10 lie relatively close to curve c ($L_e = 5,500 L_\odot$). This agrees with the results found in the previous section, where it has been concluded that the majority of the sources have an AGB luminosity of 5,500 $L_\odot$. From Fig. 10 there is good evidence that the galactic bulge Miras are the direct precursors of the more evolved OH/IR stars. In the next section we will discuss the possible range of their progenitor masses and their ages.

5.3. Initial masses of the AGB stars: age of the bulge

With the luminosity function found in Sect. 5.1 and the P-L relation found in Sect. 5.2 we can now discuss the properties of the progenitors of these stars. A most important clue to the initial masses is in the luminosity function discussed in this paper, because it reflects the core masses of stars at the end of the AGB. In Paper II, a relation between the maximum AGB luminosity and the initial mass is given. If we neglect the amount of mass that was lost before the AGB we find

$$M_i = (\varepsilon_M + 0.17) L_{max} + 0.50$$

(10)
where $M_1$ is in $M_\odot$, $L_{\text{max}}$ is in $10^4 L_\odot$, and $e_{M_1} = M_{\text{initial}} / L_{\text{max}}$. On basis of the initial mass-final mass diagram of Weidemann and Koester (1983) it was concluded in Paper II that $e_{M_1} = 1.5$ is the best compromise for main sequence masses between 1 and 10 $M_\odot$. For initial masses less than 3 $M_\odot$ it is not possible to distinguish between $e_{M_1} = 1$ and 5 (see Fig. 6 in Paper II) but it is very unlikely that $e_{M_1}$ is larger than 5 or less than 1.

In Table 8 the initial mass as a function of maximum AGB luminosity (the luminosities correspond respectively with the curves d to a in Fig. 10) is given for $e_{M_1}$ equal to 1 and 1.5 (mass loss before the AGB is neglected). For the different initial masses we have given the age of a star when it has reached the top of the AGB, for initial mass abundances equal to $Z = 0.01$, $Z = 0.04$ and $Z = 0.1$ (respectively $t_{0.01}$, $t_{0.04}$ and $t_{0.1}$). The ages are from Mengel et al. (1979), and refer to the evolution time from the ZAMS to the top of the First Giant Branch; the assumption is that any further evolution occurs in much less time.

Table 8 illustrates the importance of knowing $e_{M_1}$: for $e_{M_1} = 1$ we find initial masses that are smaller and corresponding ages that are 2 to 3 times larger than for $e_{M_1} = 1.5$. For $e_{M_1} > 1.5$ the initial masses will be larger and the corresponding ages shorter than for $e_{M_1} = 1.5$. This is easy to understand: the larger $e_{M_1}$ the larger the amount of mass that was lost for a given maximum AGB luminosity and hence the initial mass must have been larger. Together with this, the duration of the mass loss phase will increase, which means that the core mass and the luminosity at the start of the AGB mass loss phase will be lower. This can be checked with the P-L relation (Sect. 5.2).

The dashed curves in Fig. 10 are for $e_{M_1} = 1.5$. For $e_{M_1} > 1.5$ the lower end of the curves start at higher luminosities and at shorter periods, for $e_{M_1} < 1.5$ the opposite is true. For $e_{M_1} = 1$ for example the curve starts at an $M_{\odot}$ which is 0.6 mag larger. From Fig. 10 we see that there are no periods and luminosities lower than those corresponding with the lower end of the dashed curves suggesting $e_{M_1} < 1.5$. The relative small amount of stars situated at the lower end of the period-luminosity curves indicate that $e_{M_1} = 1$ is more likely to be the case than $e_{M_1} = 1.5$.

Since the majority of the AGB stars reach a maximum AGB luminosity of about $5,000 - 5,500 L_\odot$ they have initial masses between 1.1 and 1.4 $M_\odot$, where the lower limit (corresponding with $e_{M_1} = 1$) seems to be more likely. Assuming a metal abundance that is 3 times solar ($Z = 0.04$) we find a corresponding age for these stars between 7 and 15 Gyr, where the upper limit (corresponding with $e_{M_1} = 1$) is more likely. The possibility that there is small percentage (< 20%) of stars with luminosities down to $1,000 L_\odot$ cannot be excluded (Sect. 5.1). They have initial masses smaller than 1.0 - 1.2 $M_\odot$ (for $e_{M_1}$ between 1.5 and 1). If they are formed at the same time as the 1.1 - 1.4 $M_\odot$ stars they must have a significant lower metal abundance. There is also a possible tail in the luminosity distribution towards larger luminosities, but this tail does not exceed $10,000 L_\odot$. Such stars must have had initial masses as high as 1.7 - 2.2 $M_\odot$ (for $e_{M_1}$ between 1.5 and 1) and ages of order of a few Gyr, even for a very large metallicity of $Z = 0.1$. If these tails towards lower and larger luminosities really exist, and if all stars have about the same age, this implies a metallicity range of a factor of 10. Such a metallicity range has indeed been observed for M giants in the Baade windows (Whitford and Rich, 1983).

6. Post-AGB evolution in the galactic bulge

In the previous section we concluded that the Miras seen in the Baade windows and the, more evolved, AGB stars discussed in this paper, are part of the same population. After having discussed their progenitor masses, we now want to discuss the post-AGB evolution in the galactic bulge.

As discussed in Paper I, AGB stars are expected to evolve from region IIIb into region IV and finally into region V (see also Van der Veen et al., 1989). The stars in region IV are either at the very end of their AGB phase and have very long periods or have already stopped their pulsations and have left the AGB. The bolometric correction at 12 $\mu$m is still the same as for the stars of region IIIb. Because the luminosities are also the same, and the pulsations have stopped, we expect that the 12 $\mu$m flux density distribution for stars of region IV will be narrowed with respect to the 12 $\mu$m flux density distribution for stars of region IIIb. This is consistent with Fig. 5c: the only significant contribution comes from the 3-4 $\mu$m bin corresponding with a luminosity of about 5,500 $L_\odot$. This agrees very well with the result found in the previous section that the majority of the sources in region IIIb have luminosities around 5,500 $L_\odot$. The 12 $\mu$m flux density distribution in Fig. 5c almost directly (there is still a spread in distance of the individual objects) reflects the luminosity function of the stars in region IIIb; the smallness of the numbers is due to the very short life time in region IV. Very roughly Fig. 5c yields a similar luminosity distribution as suggested in Sect. 5.1: 60% of all stars have a luminosity around 5,500 $L_\odot$, 15% have lower luminosities, and 25% have larger luminosities.

The stars in region IV evolve into region V to become planetary nebulae. Their luminosity does not change, but the bolometric correction increases from 3 to about 10. Thus we expect that these objects have a 12 $\mu$m flux density distribution that is shifted towards lower flux densities. This is indeed the case as can be seen from Fig. 5d. The fact that the distribution rises from 4 to 1 Jy, where the completeness limit is around 2 Jy, indicates that the majority of these planetary nebulae have 12 $\mu$m flux densities below 2 Jy. It also suggests that the circumstellar shells become transparent in a relative short time. This is consistent with the results found by Van der Veen et al. (1989) for a sample of proto-planetary nebulae and planetary nebulae in the disk of the Galaxy.

7. Conclusions

A more accurate selection of IRAS sources situated in the galactic bulge is now possible using the IRAS two-colour diagram (Paper I). Previous attempts to select these objects (e.g. Habing, 1986) did not include a criterion for the 60 $\mu$m flux density. This has resulted in a small (10-20%) contamination of the sample with young, local, stars that are probably situated in the Ophiuchus molecular cloud region.
The galactic bulge is most obvious when we select stars with thick circumstellar shells (region IIIb of Fig. 1) and stretches out from $-15^\circ$ to $15^\circ$ in longitude and from $-10^\circ$ to $10^\circ$ in latitude. Additional infrared observations between 2 and 13 $\mu$m have been made and show that these IRAS sources have an infrared spectrum similar to those of OH/IR stars in the disk. Repeated observations have shown that the sources are variable, like the OH/IR stars in the disk, with periods between 500 and 2,000 days and amplitudes between 0.4 and 1.1 mag. At this moment more than half of them are also detected in the OH (1612 MHz) line and all show the double peaked line profile, typical for OH/IR stars.

Knowledge of the nature and the variability of the sources enables us to interpret the 12 $\mu$m flux density distribution of the galactic bulge sources in terms of their luminosity function. We find a strongly peaked luminosity function around $5,500 L_\odot$ possibly with tails going down to $1,000 L_\odot$ and going up to $10,000 L_\odot$. The maximum AGB luminosities are similar to those of the Miras observed in the Baade windows, and they fit the same $P-L$ relation: i.e. the OH/IR stars in the bulge are evolved from the Miras.

The luminosity distribution shows that the majority of the stars have had main sequence masses between 1.1 and 1.4 $M_\odot$ and are 7–15 Gyr old. The presence of stars with even lower masses, may be even lower than 1 $M_\odot$, and larger masses up to 2 $M_\odot$ cannot be excluded, although their numbers have to be small. If all these stars have the same age there must be a range in metal abundance over a factor of 10; a similar range in metal abundance follows from the observations of M giants in the Baade windows (Whitford and Rich, 1983).

The observed peak in the luminosity function around $5,500 L_\odot$ is in agreement with the luminosity distribution derived for a very small sample of stars that are just evolving from the AGB and have stopped their pulsations.

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