

Field #3 of the Palomar-Groningen survey*

II. Near-infrared photometry of semiregular variables**

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Abstract. Near-infrared photometry (JHKLM) was obtained for 78 semiregular variables (SRVs) in field #3 of the Palomar-Groningen survey (PG3, $l = 0^\circ$, $b = -10^\circ$). Together with a sample of Miras in this field a comparison is made with a sample of field SRVs and Miras. The PG3 SRVs form a sequence (period–luminosity & period–colour) with the PG3 Miras, in which the SRVs are the short period extension to the Miras. The field and PG3 Miras follow the same $P/(J-K)_0$ relation, while this is not the case for the field and PG3 SRVs. Both the PG3 SRVs and Miras follow the Sgr I period-luminosity relation adopted from Glass et al. (1995). They are likely pulsating in the fundamental mode and have metallicities spanning the range from intermediate to approximately solar.

Key words: stars: evolution – stars: AGB and post-AGB – Galaxy: center

1. Introduction

In the last decade much effort has been spent on the studies of Miras (e.g. van der Veen 1988, Feast et al. 1989, Whitelock et al. 1991, Blommaert 1992, and Glass et al. 1995), OH/IR stars (e.g. Herman 1988, te Lintel-Hekkert 1990, Lindquist et al. 1992, van Langevelde 1992, Blommaert et al. 1994, and Habing 1996), and carbon stars (e.g. Willems 1987, Chan & Kwok 1988, Willems 1988ab, Willems & de Jong 1988, de Jong 1989, Stephenson 1989, Zuckerman & Maddalena 1989, Azzopardi et al. 1991, Tyson & Rich 1991, Westerlund et al. 1991, Groenewegen et al.

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* Based on observations obtained at the European Southern Observatory, La Silla, Chile

** Table 2 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or www at URL <http://cdsweb.u-strasbg.fr/Abstract.html>

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1992, Groenewegen 1993, Marigo et al. 1996b, Ng 1997b & 1998, and Marigo 1998).

Systematic investigations of semiregular variables (SRVs) were carried out by Kerschbaum & Hron (1992, 1994; hereafter respectively referred to as KH92 & KH94) and Jura & Kleinmann (1992) in recent years. From the temperatures, luminosities, mass loss rates and number densities KH92 & KH94 distinguished a ‘blue’, ‘red’, and a ‘Mira-like’ group among their SRVs. Their result suggests an evolutionary sequence, where the ‘blue’ SRVs evolve towards the thermally pulsing AGB, change into ‘red’ SRVs, and then continue to evolve to the Mira phase.

AGB stars are ideal probes in studies of the galactic bulge, because of their high luminosities. Various photometric (Frogel & Whitford 1987, Terndrup 1988, Geisler & Friel 1992), spectroscopic (Rich 1990, McWilliam & Rich 1994, Sadler et al. 1996) and star counts (Ng et al. 1996a) studies from Baade’s Window (hereafter referred to as BW; $l = 1^\circ 0$, $b = -3^\circ 9$), show a large spread in metallicity ranging from $-1.5 < \text{Fe/H} < 1.0$. The bulge offers a good opportunity to study the evolutionary aspects of AGB-stars in relation with their metallicity, which is one of the major evolutionary parameters.

PG3 (field #3 of the Palomar-Groningen Variable Star Survey; $l = 0^\circ$, $b = -10^\circ$; see Sect. 2.1 for details) is well searched for variable stars (Plaut 1971, Wesselink 1987; the latter will hereafter be referred to as Wess87). Blommaert (1992; hereafter referred to as Bl92) studied the properties of the PG3 Miras with NIR (near-infrared) and IRAS photometry. The period-colour relation for the PG3 Miras was found to be shifted significantly from the Large Magellanic Cloud (LMC) relation (Feast et al. 1989). With the theoretical relation from Wood et al. (1991) it was concluded that this must be due to metallicity, which could be about 1.6 times larger for the PG3 Miras (Bl92). Feast (1996) obtained similar results for the Miras in the galactic bulge versus those in the LMC. Comparable indications were found by Whitelock (1996) from the local Miras.

In this study a comparison is made between the pulsation and near-infrared properties of the PG3 SRVs and Miras and

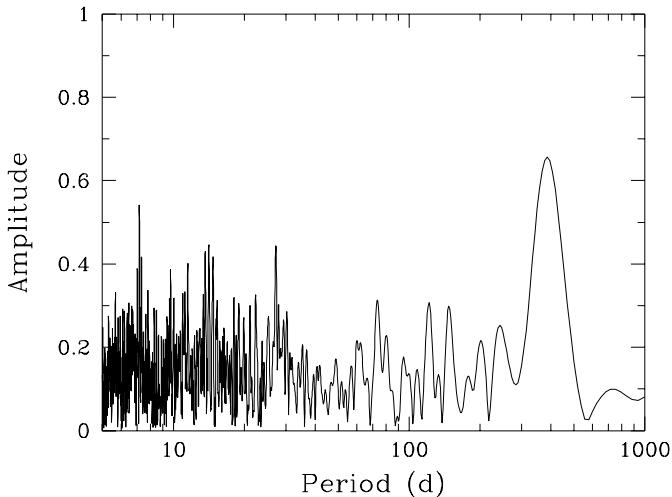


Fig. 1. The Fourier spectral window for the B_J plate coverage of PG3 (Wesselink 1987)

the field SRVs and Miras. In Sect. 2 a discussion is given about the SRV data: the observations and the comparison samples. We proceed in Sect. 3 with a description of the results of this analysis, continue with the discussion in Sect. 4 and summarize it in Sect. 5.

2. Data

2.1. PG3

Four fields were selected in the mid-fifties by Baade and Plaut to search for variable stars (Blaauw 1955; Larsson-Leander 1959). The results from the photographic survey, known as the Palomar-Groningen Variable Star survey, were published in a series of six papers (Plaut 1966, 1968ab, 1966, 1971, 1973). The centre of PG3 is located 10° south of the galactic centre and skims over the edge of the galactic bulge. Important aspects of this field are the large area covered ($6^\circ.5 \times 6^\circ.5$) and the low interstellar extinction, which is gradually increasing in the direction towards the galactic centre (Wess87).

With emphasis on the RR Lyrae stars, the variable stars in PG3 were re-examined by Wess87, using UKST B_J and R_F Schmidt plates. Fig. 1 shows the Fourier spectral window for the epochs of the B_J plates. The figure shows that a good resolution, as intended, is obtained towards the short period variables, but for the long period variables a deficiency of stars with periods between 320 to 500 days could be possible. The three highest alias peaks correspond in decreasing order with one year, one week, and one synodical month.

The large number of Miras and SRVs discovered in this field makes it very attractive, to subject these stars to a more detailed study. B192 studied a sample of Miras and compared them with the IRAS sources in PG3, while we focus on the SRVs.

Table 1. Log of the observing runs

Run	dates	year	observer(s)
1	28 Jul – 2 Aug	1990	Ng
2	21 May – 3 Jun	1991	Brown
3	20 – 29 Aug	1991	Ng
4	16 – 21 Jun	1992	Ng & Schultheis
5	29 Jun – 3 Jul	1993	Ng & Schultheis

2.2. The SRV sample

In the GCVS4 catalog (Khlopov et al. 1988) the classification of SRVs is based on the shape and the amplitude of the light curve. Generally, the period of the variations ranges from 20 to 2000 days with an amplitude less than $V = 2^m.5$. Plaut (1971) distinguished in his classification SRa and SRb type variables, while Wess87 made no distinction. Wess87 based his criteria on the B_J and R_F amplitudes, smaller than $2^m.0$, and periods ranging from ~ 30 – 1000 days. The SRV classification of Wess87 is in most of the cases compatible with a SRV of type ‘a’ (hereafter referred to as SRaV) from Plaut (1971). In general, the lightcurves of the SRaVs resemble those from the Miras. The difference in the classification is merely a consequence of the imposed amplitude limits in the variation.

In this study the SRV stars are selected with the Wess87 classification. Higher priority is given to the observations of stars with a $Q=0$ quality flag, indicating that there is no doubt about the classification and the period. The SRVs are selected such, that there is no bias to the brightest SRVs and that the sample covers in 25 days intervals the full period range.

2.3. Near-infrared photometry

Near-infrared photometry (JHKLM) of 78 PG3 SRVs was obtained with the ESO 1-m telescope, La Silla (Chile), equipped with an InSb detector. The observations were carried out under photometric circumstances in the observing seasons 1990 – 1993 (ESO N° 49.5 – 011 & 51.7 – 056). Table 1 shows the log of the observing runs. The 1990 – 1991 observations (see B192) of the stars S40, S147, S728, S969, S1008, S1016, S1128 and S1204 were carried out as part of the ESO key programme ‘Stellar evolution in the galactic bulge’ (Blommaert et al. 1990; ESO N° 45K.5 – 007). The observations were made in a standard way, through a diaphragm with a $15''$ aperture with the chopping and beam-switching technique. An 8 Hz sky chopping and a beam-switch throw of approximately $20''$ in R.A. was applied.

The JHKLM fluxes are calibrated to the ESO photometric system (Bouchet et al. 1991). The typical errors are $\sim 0^m.02$ in JHK, $\sim 0^m.1$ in L' , and $> 0^m.2$ in M. For some stars no L' and M photometry was obtained, because they were fainter than the limiting magnitude attainable with the telescope. Table 2 gives the JHKLM magnitudes of the PG3 SRVs together with the period (Wess87).

In general the limiting magnitude was $K_{lim} \simeq 10^m$ for most of our observing nights, which is due to our relatively short in-

Table 2. Near-infrared photometry for the stars in field #3 of the Palomar-Groningen Variable Star Survey (Plaut 1971). Column 1 lists the stellar identifier, adopted from Wesselink (1987); column 2 gives the identification made by Plaut (1971); column 3–7 gives the JHKLM photometry, typical errors are $\sim 0.^m02$ in JHK, $\sim 0.^m1$ in L' and $> 0.^m2$ in M; column 8 gives the observing run identifier (see table 1); column 9 gives the period determined by Wesselink (1987) if available; and column 10 gives the quality flag related with the period and the identification of the star (Q=0: no doubt about the determined period and classification, Q=1: classification is correct but alternative period is possible, Q=2: period determination is correct but the classification is doubtful, Q=3: both period determination and classification are unreliable)

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tegration time and integration sequence. Photometry for some of the fainter stars were obtained in nights when the photometric conditions allowed it. In this respect the DENIS survey (Epchtein et al. 1994, 1997), with $K_{lim} \simeq 14^m$, should be able to improve on the photometry and reach significantly deeper limits.

2.4. Crowding

The presence of additional stars in the beam cannot be avoided, because we are dealing with crowded field observations. Two cases should be considered: additional stars in the primary or in the background beam. An additional flux contribution in the primary beam would lead to an increase of the flux from the star, while stars in the background beams would give a background subtraction which is too high. As a consequence the flux of the target star will be underestimated. In first approximation, the number of faint stars in both the primary beam and the background beams are similar.

The stars in the background are in general much fainter and not as red as the stars observed. The induced errors from stars present in the background beams are expected to be less than the errors quoted above. A new position for the background subtraction would have been selected, if a bright star was noticed in one of the background beams, but this was not necessary. The flux of the target star will be overestimated with additional stars in the primary beam. Due to stars surrounding S283 (see finding chart in Ng & Schultheis 1997), the magnitudes are slightly too bright and the colours too blue for this star.

2.5. Interstellar extinction

The procedure described by Bl92 is used, to correct for the interstellar extinction. It is based on the PG3 extinction map, constructed by Wess87 from the colour excess of the RR Lyrae stars at minimum light. In this map the extinction is highest in the plate corner at lowest galactic latitude ($A(B_J) = 1.^m14$; $b = -6^\circ$) and lowest at the opposite corner ($A(B_J) = 0.^m14$; $b = -14^\circ$). The extinction is described with a linear relation, because of the smoothness of the gradient in the extinction map. In first approximation we have $A(B_J) = 0.133b + 2.02$, where b is the galactic latitude. For a normal extinction law the corrections for the different infrared passbands can be derived with the standard curve no. 15 of van de Hulst (1949). All the JHK photometry for the PG3 stars discussed in this study are de-reddened with the procedure outlined above. The photometric data in Table 2 are not de-reddened.

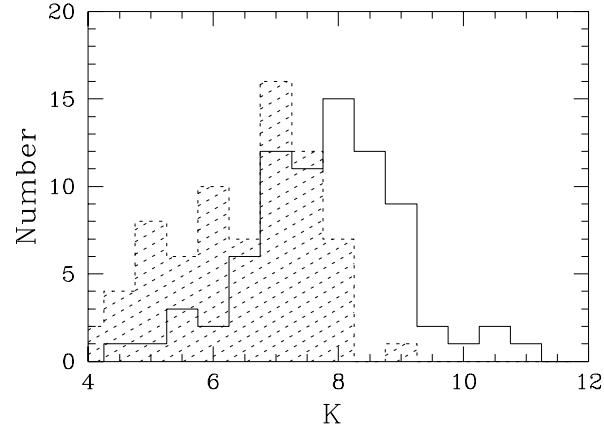


Fig. 2. Distribution of K-magnitudes for the SRVs (solid histogram; this paper) and the Miras (dot-shaded histogram; Bl92) observed in PG3

2.6. The comparison sample

A comparison is made with other near-infrared photometric studies of SRVs and Miras, in order to obtain a better understanding of the evolutionary status of the PG3 SRVs. We use a sample of PG3 Miras (Bl92), well observed O-rich field Miras (Catchpole et al. 1979) and a magnitude limited sample of field O-rich SRVs (KH94, Kerschbaum 1995). Note, that the field samples mentioned above might not be truly representative in their relative numbers for the local neighbourhood. The field stars were de-reddened with a procedure similar to Feast et al. (1982). The reddening corrections are small, because the visual absorptions ranges typically from $0.^m05 - 0.^m20$. We further used the Sgr I Miras from Glass et al. (1995) and the LMC LPVs (long period variables) from Reid et al. (1995) as an extra indication. For the latter we defined Mira & SRV variable groups, following Hughes & Wood (1990) on basis of the I-band amplitudes. We use the Reid et al. data set instead of the Hughes & Wood data set, because the former are in the same photometric system as the Sgr I Miras.

2.7. Photometric transformations

The photometry of the PG3 SRVs & Miras and the field SRVs are in the ESO photometric system (Bouchet et al. 1991, van der Blieck et al. 1996). The photometry for the field Miras was obtained in the SAAO photometric system as defined by Glass (1974). This photometric system is not identical to the SAAO system in which the photometry for the Sgr I Miras, the LMC

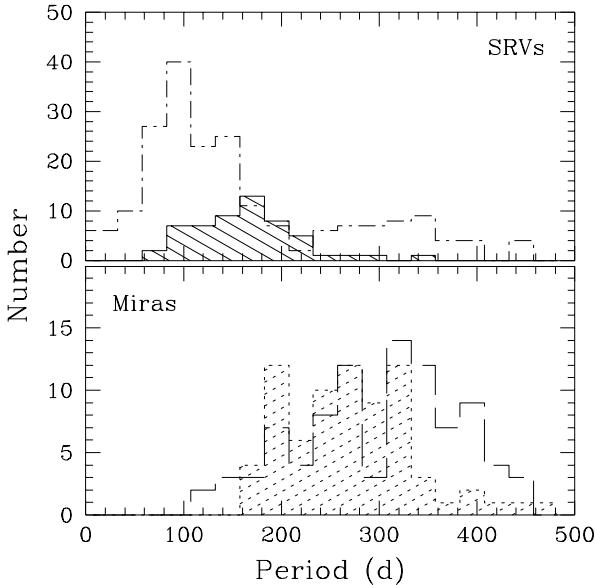


Fig. 3. Period distribution for the SRVs (solid, shaded histogram; this paper) and the Miras (dot-shaded histogram; Bl92) observed in PG3 together with the distributions for the field SRVs (dot-dashed histogram; KH94 and Kerschbaum 1995) and Miras (long dashed histogram; Catchpole et al. 1979)

LPVs, and the period-luminosity & period-colour relations were obtained (Glass et al. 1995). All the photometry discussed in this paper are in the ESO photometric system (Bouchet et al. 1991) or transformed to it from the various SAAO systems. New transformations from Hron et al. (1998) are used, because existing transformations either refer to the old ESO system (Bessell & Brett 1988, Carter 1990, Engels et al. 1981, Wamsteker 1981) or do not cover all SAAO systems (Bessell & Brett 1988, Bouchet et al. 1991, Carter 1990, van der Blieck et al. 1996). Furthermore, these transformations do not include stars with $(J-K) > 1^m0$. Extrapolation of these transformations to the colours of typical AGB stars leads to errors of the same order as e.g. the differences due to metallicity (Hron et al. 1998). The estimated uncertainties in the new transformations are typically $\sim 0^m02$ in the colours.

3. Results

The observations are presented in Figs. 2–8a and b. The mean magnitude is used in the figures, when several observations are available for a star. In Figs. 4–8a and b only those stars are considered which, according to Wess87, are classified correctly and have a good period determined.

3.1. Magnitude distribution

At present we are mainly interested in the bulge stars. Therefore, disc stars are referred to as the foreground contamination.

If the stars were located in the disc, the magnitude distribution of the foreground contamination in PG3 will show a gradually, more or less linear, increase towards fainter magnitude (see for example Fig. 11–4, Ng et al. 1995). The roughly

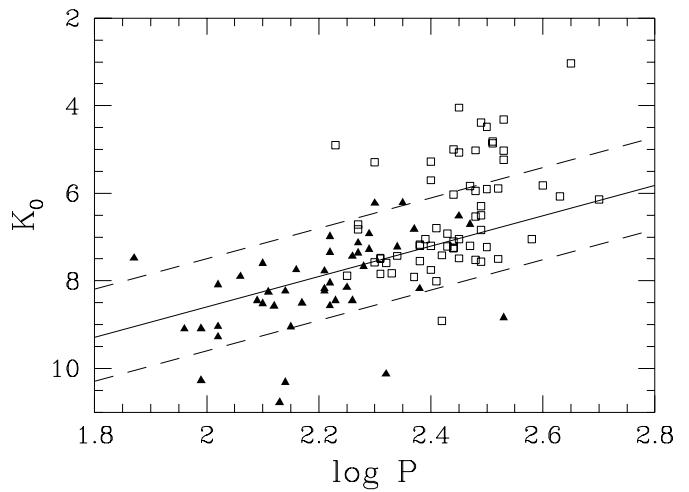


Fig. 4. K_0 vs $\log P$ relation for the PG3 SRVs (solid triangles; this paper) and PG3 Miras (open boxes; Bl92). The straight line shows the Sgr I relation given by Glass et al. (1995). The two dashed lines indicate the transition between bulge and non-bulge stars (see Sect. 3.3 for details)

linear increase is a consequence of the increasing volume in the cone, when sampled towards larger distances. The distribution of stars in the bulge have in first approximation a peaked shape (see for example Fig. 11–3, Ng et al. 1995). This is a result of the density profile of the bulge stars, which increases towards the galactic centre, is highest near the galactic centre, and decreases afterwards.

Two interpretations are possible for the K -magnitude distributions displayed in Fig. 2.

1. There is a difference in the distribution of the foreground contamination ($K < 6^m0$), between the SRVs and Miras. The foreground contamination of the Miras appears to be significantly larger than for the SRVs. The large fraction of foreground Miras was already noticed by Bl92, especially those which also have an IRAS 12 μm and 25 μm detection. Moreover, Fig. 2 shows that the peak of the SRVs ($6^m5 < K < 9^m0$) is about 1.5 times broader than the Mira peak between $6^m5 < K < 8^m0$. This could indicate that part of the SRVs with $6^m5 < K < 8^m0$ are in fact Mira type variables. They were classified as SRVs, because of the amplitude of the variations in the lightcurves. In this case some of the SRVs with $K > 8^m0$ represent a group of intrinsically fainter stars.

2. All the PG3 SRVs represent a group of stars with a distribution similar, but intrinsically fainter, to the Miras. A 1^m0 shift towards brighter magnitudes is an empirical patch for the luminosity difference between SRVs and Miras. With this shift the foreground contamination for the SRVs is slightly smaller, but probably the difference is not significant anymore. In this case the PG3 SRVs are also contaminated with foreground stars.

In Sect. 4.6 we argue that the latter possibility is preferred, but that a fraction of the foreground contamination might be associated with the galactic bar.

3.2. Periods and amplitudes

Fig. 3 gives the period distributions of the various samples, used for comparison with the PG3 SRVs. The PG3 SRVs have periods comparable with the short period tail of the PG3 Miras. Their periods further overlap with the 'red' field SRVs distinguished by KH92 & KH94, but the PG3 SRVs have however a longer mean period.

There is no significant difference between the period distribution of the field and PG3 Miras, except for a deficiency of PG3 variables with periods larger than 300 days and is due to the spectral window for which the B_J plates (Wess87) were taken, see Sect. 2.1.

The mean photo-visual amplitude, estimated from Plaut (1971), for the PG3 SRVs is about $1.^m1$. This is comparable to the V-amplitude of the field SRVs in the same period range, but much smaller than the amplitudes for the field Miras ($5.^m5$).

3.3. Period – K relation

Fig. 4 shows the apparent K magnitude versus $\log P$ diagram (hereafter referred to as PK_0 -relation). The PG3 SRVs obey the same PK_0 -relation as the PG3 Miras (Schultheis et al. 1996). This figure suggests a common origin for the two samples. Note that the straight line in Fig. 4 is not a fit to the data! It shows the PK_0 -relation for Sgr I (Eq. 5, Glass et al. 1995), transformed from the SAAO to the ESO photometric system. We further adopted an extinction ($A_V = 1.^m71$ instead of $A_V = 1.^m87$) for the Sgr I field. The resulting PK_0 -relation for Sgr I in the ESO photometric system is: $K_0 = -3.47 \log P + 15.54$. The dashed lines above and below the Sgr I relation ($\pm 1^m$) are a combination of the expected scatter due to the depth of the bulge ($^{+0.5}_{-0.6}$ mag) and the dispersion in the magnitudes (not averaged, $\pm 0.^m6$) of the PG3 variables. The stars above the dotted line are foreground stars, but see Sect. 4.6 for additional comments. A few stars lie under the period-luminosity relation. Ng & Schultheis (1997) argue that those stars are located at the edge of the Sagittarius dwarf galaxy. In the further analysis only those stars, which are located between the two dashed lines, are considered.

3.4. Period - colour relation

In Figs. 5a-c the period-colour (PC) relations for the PG3 SRVs and Miras are shown for $(J-K)_0$, $(J-H)_0$, and $(H-K)_0$, respectively. The thick straight lines indicate the LMC relation due to Feast et al. (1989) and Glass et al. (1995). In Fig. 5a all the stars are slightly offset above the $P/(J-K)_0$ relation. In Fig. 5b the Miras are below the $P/(J-H)_0$ relation, while the SRVs are located slightly above. The $(J-H)_0$ colour for both the SRVs and Miras appears to be independent of the period. In Fig. 5c the PG3 SRVs appear to follow the LMC relation, while the PG3 Miras are offset above. It is also possible that a fraction of the SRVs follows the PG3 Mira $P/(H-K)_0$ relation, which is steeper than the LMC relation. An other fraction of SRVs lies clearly above such a relation.

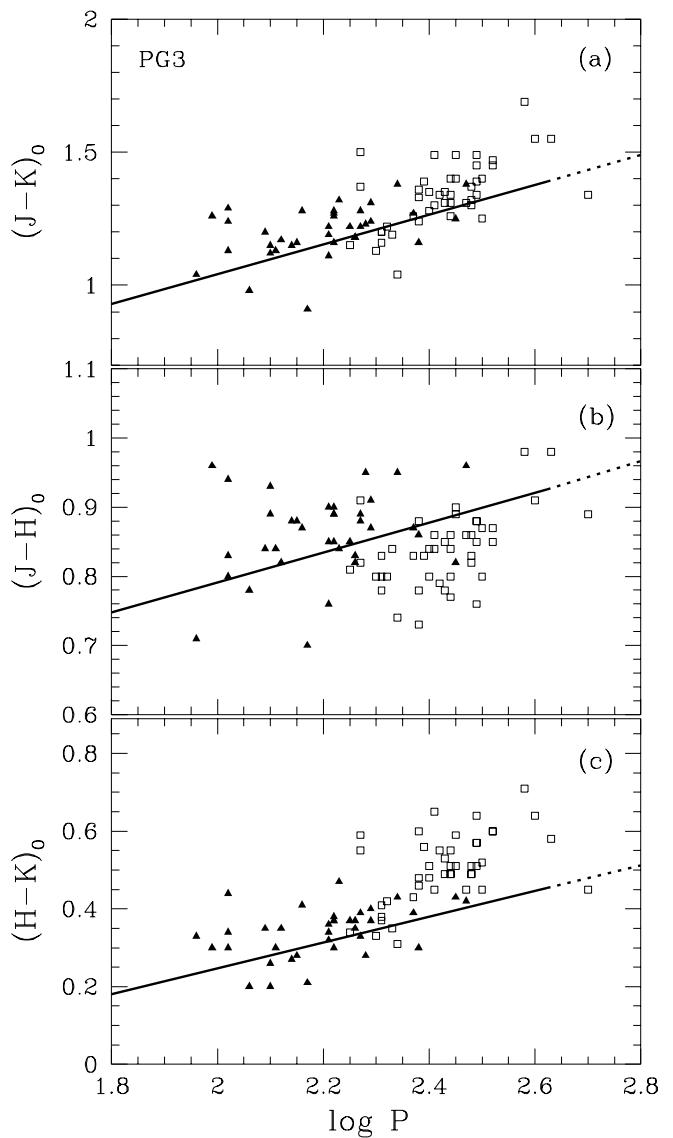


Fig. 5a–c. Colour vs $\log P$ relations for the PG3 SRVs & Miras for respectively **a** $(J-K)_0$, **b** $(J-H)_0$, and **c** $(H-K)_0$; only bulge stars are considered and the symbols are the same as those used in Fig. 4. The thick straight lines are the LMC relations (Glass et al. 1995) transformed from the SAAO(Mk3) to the ESO system (see Sect. 2.7). The dotted extension indicate an extrapolation of this relation for $P > 420^d$

For the PG3 Miras the mean offset from the LMC PC-relation is $\sim 0.^m05$. Within the transformation uncertainty of the LMC relation this is comparable to the $\sim 0.^m07$ offset obtained by Bl92.

Fig. 6 shows the $P/(J-K)_0$ relation for the field SRVs and the field Miras. The field Miras also follow the LMC relation, although there is a slight offset of $\sim 0.^m03$ towards redder $(J-K)_0$. This offset is not conclusive with regard to possible differences to the LMC or PG3 stars, given the transformation uncertainties (field Mira and the LMC relation).

The $0.^m05$ offset of the PG3 Miras translates with the theoretical period-colour relation from Wood et al. (1991; assuming com-

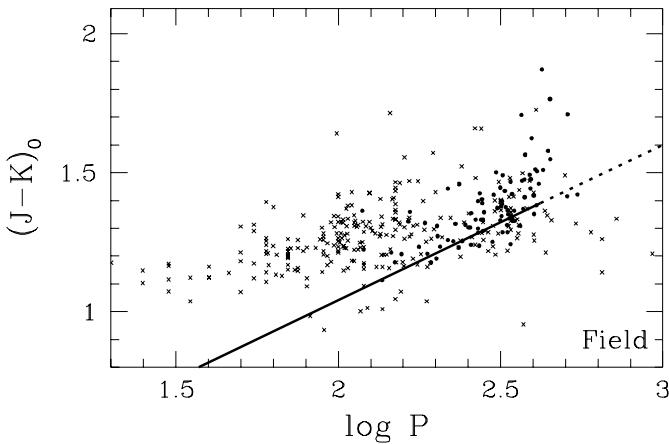


Fig. 6. (J-K)₀ vs log P relation for the field SRVs (crosses; KH94 and Kerschbaum 1995) and field Miras (filled circles; Catchpole et al. 1979). The thick straight line is the LMC relation due to Glass et al. (1995). The photometry of the field Miras and the LMC relation are transformed respectively from the SAAO(Mk1) and SAAO(Mk3) to the ESO system (see Sect. 2.7)

parable masses between the PG3 & the field versus the LMC Miras) in a mean metallicity of the PG3 and field Miras ~ 1.4 times as high as the LMC.

The majority of the field SRVs appear to follow a different PC-relation with a slope flatter than the field Miras. But this might be an artifact, if the field SRVs are a non-homogeneous sample of fundamental mode pulsators with longer periods and overtone pulsators with shorter periods. Since each mode has its own PC-relation, their combined distribution could well result in the flatter slope.

3.5. Colour - magnitude diagram

Fig. 7 shows the (K,J-K)₀ CMD for the PG3 SRVs and Miras. Isochrones placed at 8 kpc distance for 5 and 10 Gyr old stellar populations with Z=0.004 and Z=0.020 are displayed in this figure. The isochrones from Bertelli et al. (1994) are used. They converted their isochrones from the theoretical to the observational plane by convolving the near-infrared bands, as provided by Bessell & Brett (1988), with the spectral energy distributions from Kurucz (1992) for temperatures higher than 4000 K. At lower temperatures they used observed spectra as described in Sect. 4 of Bertelli et al. (1994) and they combined the effective temperature scale from Ridgway et al. (1980) for the late M giants with the Lançon & Rocca-Volmerange (1992) scale for the early M giants. The lack of very red standards limits the near-infrared colour transformations (Bressan & Nasi 1995) and causes the colours of the Z=0.02 isochrones to ‘saturate’ around (J-K)₀ $\simeq 1.35$. We derived a new, empirical $T_{\text{eff}}\text{--}(J-K)_0$ colour relation by making a conservative fit through the T_{eff} and (J-K)₀ data available for cool giants (see Ng et al. 1998 for details). This relation was adopted to compute the near infrared colours of the isochrones shown in Fig. 7.

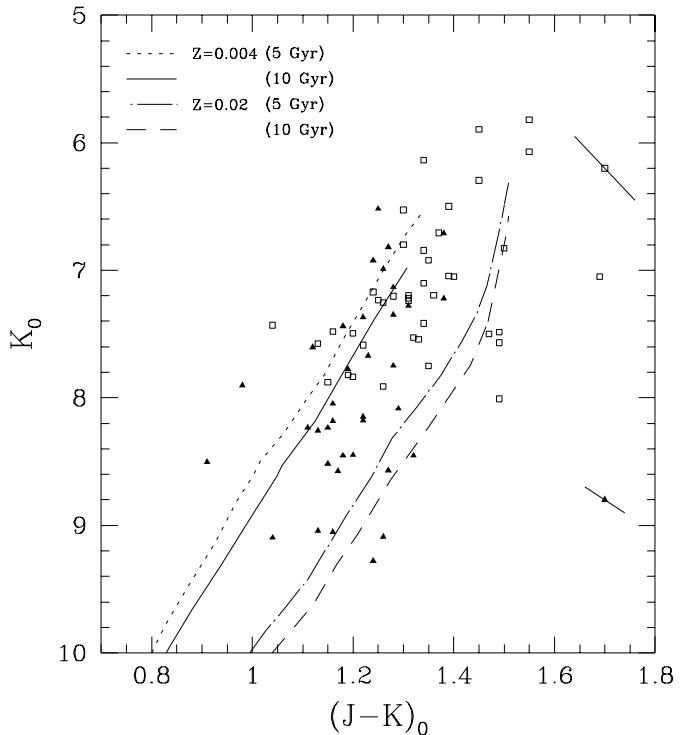


Fig. 7. K₀ vs (J-K)₀ Colour-Magnitude Diagram for the PG3 SRVs and Miras, the symbols are the same as those used in Fig. 4. The ‘error’ bars attached to the two symbols on the right side indicate the effects of variability, the symbols do not correspond to the actual data. Isochrones (Bertelli et al. 1994), placed at 8 kpc distance (Wesselink 1987, Reid 1993), are shown for 5 and 10 Gyr populations with Z=0.004 and Z=0.020. The near-infrared colours of those isochrones have been computed with an empirical $T_{\text{eff}}\text{--}(J-K)_0$ colour relation, see Ng et al. (1998; Table 1) for details about this relation.

The SRVs and Miras follow the trend indicated by the isochrones. SRVs and Miras with similar age and metallicity, distributed around isochrones with comparable age and metallicity, belong to the same population. Note that variability moves the stars in an almost diagonal direction in the CMD. The upper limits for the variation of the J-K colour around the light cycle is about $\sim 0.^m 20$ for a Mira and $\sim 0.^m 10$ for a SRV (Hron & Kerschbaum 1994). For the SRVs the amplitudes are too small to explain the scatter, while for the Miras the scatter might be for a large fraction due to their variability. The uncertainties in the interstellar reddening is according to Wess87 in the worst case $0.^m 17$ in B_J, which translates in $\sim 0.^m 02$ in K and $\sim 0.^m 03$ in J-K. Interstellar reddening therefore cannot explain the observed spread of $\sim 0.^m 20$ in J-K. This spread on the other hand might be related to the intrinsic width of the instability strip. The intrinsic spread of the LMC PC relation provides an upper limit. According to Kanbur et al. (1997) this spread amounts for oxygen rich stars to $0.^m 11$ in J-K. This is again smaller than the observed colour spread.

Independently the variability of the SRVs, the uncertainties in the interstellar reddening and the intrinsic width of the instability strip cannot account for the observed colour spread. In

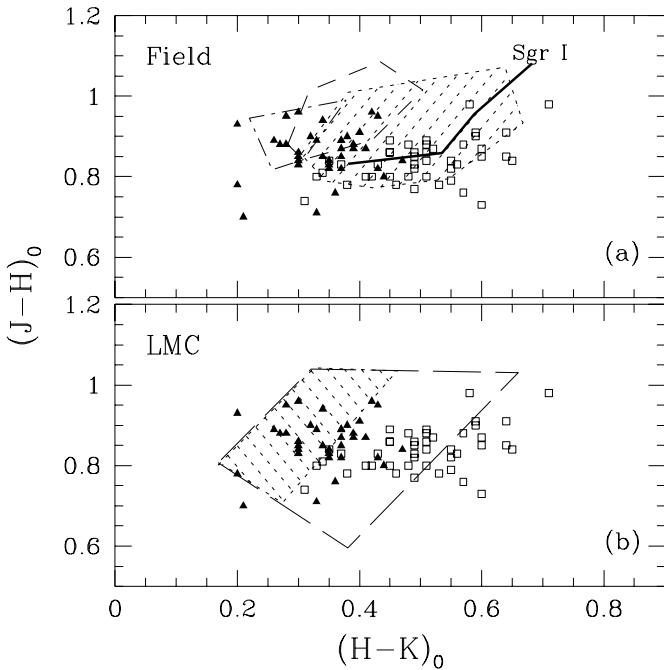


Fig. 8a and b. $(J-H)_0$ vs $(H-K)_0$ Colour-Colour Diagram for the PG3 SRVs and Miras, the symbols are the same as those used in Fig. 4. The polygon boxes show the location of the SRVs and Miras in different galactic environments: **a** Field and **b** LMC. In frame **a** the solid line represents the location of the Sgr I Miras by Glass et al. (1995), the dot-shaded box the Miras (Feast et al. 1989), the dot-dashed box the ‘blue’ SRVs and the long-dashed box the ‘red’ SRVs (KH92 & KH94). In frame **b** the dot-shaded box represents the approximate location of the SRVs and the solid box the Miras from the Reid et al. (1995) LPVs (see Sect. 2.6)

combination even an upper limit for the colour spread, which amounts to $0.^m15$, is not sufficient to explain the observed scatter.

The isochrones show that the effect of a 5 Gyr age difference results merely in a shift of $\sim 0.^m04$ in the $(J-K)_0$ colour. On the other hand, metallicity differences result in larger shifts in the $(J-K)_0$ colour, e.g. $\sim 0.^m20$ in Fig. 7. One might argue that the depth of the bulge would invalidate an analysis with isochrones, but one can verify easily that a similar result is obtained by removing the differential distance effects. For example, through an absolute calibration of the magnitude from the periods of the variables with the PK_0 -relation at the distance of the galactic centre, i.e. 8 kpc (Wesselink 1987, Reid 1993). The reason for the similarity of the result is that it depends strongly on the colour range covered and less on the magnitude (apparent or absolute) of the stars.

The presence of a large spread in the metallicity could explain the distribution of the stars in the CMD. Due to the large spread in metallicity it is not possible to get a reliable age estimate. The red edge is due to stars around solar metallicity, while the stars at the blue edge have $Z=0.004$.

3.6. Colour – colour Diagram

The colour-colour diagram in Fig. 8a and b demonstrates the difference between the Miras and SRVs in PG3. For comparison the different locations of the Sgr I Miras (Glass et al. 1995; note that we adopted an extinction in agreement with $R_0=8$ kpc, see also Sect. 3.3), the LMC LPVs (Reid et al. 1995) and the field Miras and SRVs (Feast et al. 1989, KH92 & KH94) are indicated. However, the shape of the LMC box is not well defined due to the small number of stars used present in the region $(J-H)_0 < 0.^m8$. The PG3 SRVs are shifted with respect to the PG3 Miras to bluer $(H-K)_0$ and slightly redder $(J-H)_0$.

From the large similarity in period and amplitude between field ‘red’ SRVs and PG3 SRVs one might expect that the PG3 SRVs will be located in the region of the ‘red’ field SRVs. Although there is some overlap, the PG3 SRVs appear to be on average bluer in both colours than the ‘red’ field SRVs. The PG3 SRVs extend to redder colours than the LMC SRVs

The PG3 Miras are more similar to the Sgr I Miras than to the comparison samples of field and LMC Miras. The PG3 stars do not extend to $(J-H)_0$ colours as red as the Sgr I Miras. This could be related with deficiency of PG3 Miras with periods longer than 320 days. Within the uncertainties in the adopted colour transformations PG3 and Sgr I are comparable to each other.

For $(J-H)_0 \lesssim 0.^m75$ and $(H-K)_0 \lesssim 0.^m50$ the LMC is compared to the field and PG3 abundant with relatively blue LPVs/Miras. In addition, the LMC and the field have in contrast to PG3 and Sgr I for $(J-H)_0 \gtrsim 0.^m90$ and $(H-K)_0 \lesssim 0.^m60$ in this region a significant number of LPVs/Miras. In the following section we will argue that this is due to a combination of age and metallicity of the stars.

4. Discussion

4.1. Miras: PG3 versus field, Sgr I and LMC

In Fig. 8a and b the PG3 Miras resemble more the Sgr I Miras than the field Miras and LMC LPVs. This is apparently in contradiction with Glass et al. (1995, Fig. 4c) who did not find any significant offset of the Sgr I Miras from the LMC $P/(J-K)_0$ relation. Note however, that the extinction correction is actually the origin of this discrepancy. Using $A_V=1.^m71$ the Sgr I Miras will be $0.^m03$ redder in $(J-K)_0$. The estimated offset is now $\sim 0.^m04$ and within the uncertainties comparable to PG3.

From Figs. 5a and 6 it is not clear if there is a significant offset from the field Miras with respect to either the LMC or PG3, while there is an offset between PG3 and the LMC. Fig. 8a and b however shows that the field and PG3 Miras are not comparable and that there are noticeable differences between all four groups of Miras: (i) in contrast to PG3 and Sgr I, the field and LMC Miras populate the region with $(J-H)_0 \gtrsim 0.^m90$, (ii) the PG3 Miras extend to redder $(H-K)_0$ colours than all the other groups, and (iii) only the LMC Miras reach $(J-H)_0 \lesssim 0.^m75$.

The blue $(J-H)_0$ limit of the LMC Mira box is only defined by a few objects. The last point above is probably not a real difference but induced by statistical fluctuations. Note that

unidentified, hot carbon stars in the Reid et al. (1995) sample would be located in this area of the colour-colour diagram (see for example Fig. 5 from Costa & Frogel 1996). However, the Reid et al. stars are LPV's while the blue carbon stars are not known to be large amplitude variables and nothing is known about the variability of the blue carbon stars. This point can be clarified only by more observational data.

Statistical fluctuations can hardly be responsible for the other two differences between the four groups of Miras. The redder $(H-K)_0$ colours of the PG3 Miras could be due to metallicities higher than solar but there is no evidence for this from the colour magnitude diagram. The majority of the field stars with solar metallicity have ages between 1 Gyr and 8 Gyr (see Figs. 3 & 4 from Ng & Bertelli 1998), while for PG3 our age estimates range from 5 Gyr to 10 Gyr (Sect. 3.5, Ng et al. 1995). Thus the redder colour could be due to an older age of the PG3 stars with $Z \simeq 0.02$.

The lack of PG3 stars with $(J-H)_0 \gtrsim 0^m 9$ and $(H-K)_0 \lesssim 0^m 5$ cannot be accounted for by metallicity effects alone, because this region is populated in the field as well as in the LMC. Age differences might again be the reason. In the LMC the last major star formation occurred 6–8 Gyr ago in some regions, while in other it happened only 2–3 Gyr ago (Vallenari et al. 1996ab). For field stars with $Z=0.008$ the age ranges from 2–10 Gyr (see again Figs. 3 & 4 from Ng & Bertelli 1998). Thus the lack of PG3 stars could be due to a lack of stars with a metallicity in the range $Z \simeq 0.008$ and an age between 2–5 Gyr.

Although age is an attractive parameter to explain the differences between the various groups of Miras we want to emphasize that confirmation through a comparison with isochrones in the colour-colour diagram is still needed. This requires a proper calibration of the colours for the isochrones, possibly combined with an improved description of the AGB-phase (Ng et al. 1998).

All together the data are compatible with a metallicity range spanning from a quarter solar to approximately solar for the field and PG3 stars. The majority of the field stars with metallicities around solar may be considerably younger than their counterparts in PG3. This would explain the smaller colour offset of the field Miras from the LMC $P/(J-K)_0$ relation in comparison to the colour offset for the PG3 Miras. In this respect the apparent bluer $(H-K)_0$ colour in Fig. 8a and b of Sgr I versus PG3 might be an indication for a slightly younger age for the Miras in the Sgr I area.

4.2. SRVs: PG3 versus field and LMC

The PG3 SRVs are similar to 'red' field SRVs in their periods and amplitudes. There are however marked differences: the slope of the PK_0 and $P/(J-K)_0$ relations for the PG3 SRVs is similar to that of the PG3 and LMC Miras, while this does not appear to be the case for the field SRVs (see KH92 and Fig. 4). In addition, the colours of the PG3 SRVs are slightly bluer than those of the 'red' field SRVs. The most plausible explanation for the colour differences is a higher temperature of the PG3

SRVs compared to the field SRVs. A temperature difference could explain the different behaviour in the $P/(J-K)_0$ relations, as outlined in Sect. 4.3.

The longer mean period of the PG3 stars is probably due to the larger homogeneity of this sample relative to the field stars. This homogeneity concerns both the variability classification and the pulsation mode (see below).

The result that the PG3 SRVs extend to redder colours than the LMC SRVs is due to their higher average metallicity.

4.3. SRVs versus Miras

Most field SRVs with pulsation periods below $\sim 200^d$ are cooler and partly brighter than field Miras with the same period (see Fig. 6 and KH92). This favours fundamental mode pulsation for the Miras and overtone pulsation for the SRVs. Similar evidence for variables in the LMC was presented by Wood & Sebo (1996, hereafter WS96). Their results indicate that the fundamental mode pulsation is consistent with stellar masses $\lesssim 2M_\odot$. This might be in contradiction with the results obtained by van Leeuwen et al. (1997). Their analysis indicate that the majority of the Miras are first overtone pulsators. However, their sample did not include SRVs and is furthermore biased to stars with large radii. For stars in fundamental mode with shorter periods (like the PG3 SRVs) the data for the smaller radii are lacking, due to observational limitations. Therefore, the results from van Leeuwen et al. are not necessarily in disagreement with WS96.

An interpretation of the PG3 stars in terms of pulsation modes has to be in agreement with the behaviour of the SRVs and Miras in the PK_0 and $P/(J-K)_0$ diagrams. The PG3 SRVs would be brighter and redder than the Miras at a given period, if the PG3 Miras are fundamental mode pulsators and the PG3 SRVs are overtone pulsators. If Miras and SRVs pulsate in the same mode, a systematically lower metallicity of the SRVs would increase their temperature and make them bluer, but at the same time their periods would be smaller at a given luminosity. This would introduce a luminosity difference relative to the Miras at a given period but would only shift the SRVs along their $P/(J-K)_0$ relation.

Therefore, our result that the PG3 SRVs are an extension of the PG3 Mira PK_0 and $P/(J-K)_0$ relations, can only be explained by adopting the same metallicity range and pulsation mode for the Miras and SRVs. In view of the similarities between field and PG3 Miras, fundamental mode pulsation is more plausible for the PG3 stars.

In addition, we conclude that the PG3 SRVs are *not* the analogs of the field SRVs (see Figs. 5a–c & 6).

4.4. The metallicity of PG3 Miras and SRVs

From star counts and metal-rich globular cluster studies (Ng 1994; Bertelli et al. 1995, 1996; Minniti 1995) one expects a gradient of metal-rich stars towards the galactic centre. BW is located closer to the galactic centre and has a larger number of high metallicity stars with respect to PG3 (Ng et al. 1996a,

1997). The period-colour relation indicates that the mean metallicity of the PG3 variables is about 1.4 times larger than the LMC mean metallicity. A comparison of both the PG3 and Sgr I (Glass et al. 1995) period-(J-K)₀ relation relative to the LMC relation shows that a small trend might be present. But the uncertainties in the extinction correction for Sgr I are larger than in PG3. An uncertainty in the extinction of $\sim 0.^m1 - 0.^m2$ in one filter would give an error in the colour, i.e. (J-K)₀, of a few hundredth of a magnitude. Together with the uncertainties in the transformation, the remaining difference between Sgr I and PG3 period-colour relation is not significant to conclude from the present data, that there is a metallicity gradient towards the galactic centre.

The PG3 SRVs and Miras extend to redder (H-K)₀ than the LMC LPVs. This indicates that the mean metallicity for the PG3 LPVs is slightly larger than for the LMC which is also consistent with Fig. 7. The bulk of PG3 Miras cover the same position as the Sgr I Miras by Glass et al. (1995). They should have a similar age and metallicity as the Sgr I Miras, which presumably have solar-type metallicity. This implies that the whole metallicity range from intermediate to solar is possible in PG3 and the LMC, but as mentioned in Sect. 4.1 there are perhaps differences in age between PG3 and LMC stars of comparable metallicity.

4.5. Hints from galactic structure

The field SRVs have a scale height of 230 pc (KH92). This is slightly smaller than the scale height of 260 ± 30 pc for the PG3 Miras with a detection in IRAS (B192). These values are comparable with the 250 pc obtained by Habing (1988) for AGB stars and they are consistent with the scale height for disc giants. The whole PG3 Mira sample, on the other hand, has a scale height of 300 ± 50 pc. Although the previous values are within the uncertainties one has to consider, that differentially there is a noticeable difference between the Miras with and without an IRAS detection. With the ages and scale heights, determined for the stellar populations in the disc (Ng 1994; Ng et al. 1995, 1996a, 1997), the age of the field SRVs and the PG3 Miras with an detection in IRAS is between 4.5–7.0 Gyr with a metallicity ranging from $Z = 0.008 - 0.015$. The age range for the whole PG3 Mira sample is estimated 4.5–7.5 Gyr. These ages appears to be in agreement with an age considerably less than 10 Gyr, estimated by Harmon & Gilmore (1988) for the bulge IRAS sources with initial masses larger than $1.3 M_{\odot}$. But Whitelock et al. (1991) showed, that their lower limit estimate for the initial mass is more likely an upper limit for the majority of the stars. This gives a lower age limit ~ 4 Gyr (Bertelli et al. 1994), which is consistent with the age deduced from the scale heights.

The very large metallicity spread causes that age estimates are very susceptible. Even ages as old as 16 Gyr estimated by B192 are possible. With such an old age the bluest SRVs and Miras should be very metal-poor. This would lead to a contradiction that long period variables cannot be present, because they are not found in old, metal-poor globular clusters. Therefore, the PG3 Miras and SRVs cannot be old and very metal-poor, but this does not rule out the intermediate and solar metallicity

cases. The period for the PG3 Miras ranges from 180–320 days, which is comparable with the periods of the Miras found in metal-rich globular clusters (Feast & Whitelock 1987, Whitelock et al. 1991). The 8–9 Gyr age of these clusters (Ng et al. 1996cd) gives an initial mass of about $1 M_{\odot}$, which is consistent with the upper limit obtained from the scale height for these stars.

On the other hand, if the disc density towards the galactic centre is lower than expected from a double exponential density profile (Bertelli et al. 1995; Kiraga et al. 1997; Ng 1994 & 1997a; Ng et al. 1995, 1996a; Paczyński & Udalski 1997; Paczyński et al. 1994), this could imply that the PG3 SRVs and Miras are not due to a disc population. As argued above they are also not related to a very old, metal-poor population. With an upper age of about 8 Gyr, the PG3 Miras are in that case likely related with the ‘bar’ population identified by Ng et al. (1996ab). The age and metallicity spread for this population ($t = 8 - 9$ Gyr; $Z = 0.005 - 0.03$) might imply that the variables in PG3 are located in the outer regions of the ‘bar’. A complication is that one should be careful with the semantics related with the ‘bar’. If the stars of this population can be found in PG3, i.e. ~ 1.5 kpc out of the galactic plane, this population cannot be originating from a bar as found in bar-like galaxies. Strictly spoken, this should be referred to as a triaxial structure.

The bluest SRVs and Miras might have a metallicity of $Z \simeq 0.005$ with an age ~ 9 Gyr. Although the uncertainty in the ages is between 1–3 Gyr, the large metallicity spread seems to indicate that all ages between 5–10 Gyr are possible in the metallicity range $Z = 0.005 - 0.03$. The great similarity in Fig. 8b between the distributions of the variables from PG3 and the LMC suggests a comparable age and metallicity for both samples. Vallenari et al. (1996ab) find indications for enhancements of the star formation rate in the LMC at ages as old as 6–8 Gyr, but in other regions the bulk of star formation has occurred only 2–3 Gyr ago.

This raises the question if stars younger than 5 Gyr are present in the galactic bulge/bar. The bluer (J-H)₀ colour of the Sgr I Miras with respect to those from PG3 might indicate a younger age for the former, but as pointed out in Sect. 3.6 the colour difference is probably due to uncertainties in the colour transformations.

The presence of carbon stars could be an indication for a young age, because the work from Marigo et al. (1996ab and references cited therein) indicates that carbon stars cannot be much older than 4 Gyr. The carbon stars (L199, S283) identified in our sample of LPVs and those identified by Azzopardi et al. (1991) might therefore be an indication for the presence of stars younger than 5 Gyr in the bulge/bar. Ng & Schultheis (1997) argue that S283 is actually related to the Sagittarius dwarf galaxy found by Ibata et al. (1994). Possibly the same argument holds for PG3 variable L199. Furthermore it was argued that the sample of carbon stars from Azzopardi et al. (1991) is probably not associated with the bulge. In the bulge they would be bolometrically $\sim 2.^m5$ too faint, but associated with the Sagittarius dwarf galaxy their luminosities are comparable to carbon stars found in other dwarf galaxies.

If all the bulge carbon stars are related to the Sagittarius dwarf galaxy (Ng 1997b, 1998) this would imply that they are absent in the bulge. In contrast to the field and LMC sample this implies the absence of a major star formation epoch less than 4 Gyr ago.

4.6. PG3 and the foreground stars

As already described in Sect. 3.1 the foreground contamination of PG3 Miras is either significantly larger or comparable with the PG3 SRVs. Fig. 7 hints that both groups belong to the same population and a similar fraction of foreground stars is therefore expected. This implies that the SRVs are one magnitude fainter than the Miras. The K magnitude distribution of the two groups are in this case comparable. The asymmetry suggests that more stars are found nearby. This could imply a high foreground contamination as suggested by BL92, but most likely it is due to stars located in the nearby side of the triaxial structure mentioned above. Some of the nearby stars in the sample belongs therefore to the same population as the bulge SRVs and Miras and should not have been treated as foreground contamination.

5. Summary

- We have shown that PG3 SRVs are not the analogs to the field SRVs. The comparison of the $P/(J-K)_0$ relation of the two SRV groups shows that they do not obey the same $P/(J-K)_0$ relation. In addition their location in a colour-colour diagram differs slightly. All together this indicates a different nature between the two SRV groups.
- The PG3 SRVs form a short period extension to the Miras PK_0 and PC -relations. This indicates that the PG3 Miras and SRVs are both pulsating in the same mode, possibly the fundamental.
- The field SRVs (the ‘blue’ and the majority of the ‘red’ group) are likely overtone pulsators.
- The metallicities of the PG3 SRVs and Miras span the range from intermediate to approximately solar.
- The age possibly covers a range from 4–10 Gyr. From the absence of LPVs in metal-poor globular clusters it is argued that the PG3 SRVs and Miras in the bulge are likely not older than 10 Gyr. From the upper mass limit of the bulge IRAS sources and the possible absence of bulge carbon stars one obtains a lower age limit of 4 Gyr.
- Field and PG3 Miras follow the same $P/(J-K)_0$ relation and cover the same region in the $(J-H)_0$ vs $(H-K)_0$ diagram. Therefore, the metallicity of the field and PG3 Miras should overlap each other. The Miras and SRVs in PG3 follow the Sgr I PK_0 -relation. This confirms independently the work of Whitelock et al. (1991) and Glass et al. (1995): they found no difference in the PL-relation for different galactic environments.

The following question arises: are there SRVs in PG3, similar to those found in the disc? The presence or absence of these stars might provide an indication of the age of the stars in PG3. The missing SRVs might be hidden among the irregular variables. According to Wess87 those are variable stars with little or

no trace of periodicity for which the amplitudes do not exceed 1^m5 . For verification, a detailed study of these stars is desired.

Another question which arises concerns the nature of the large spread in metallicity. The large range of ages seems to indicate that both young and old stars can be present with intermediate up to solar metallicity. Even the presence of more massive, young stars, which can be metal-poorer than older stars, is possible. In a closed box model one expects an increasing metallicity towards younger ages. Is this an indication that a closed box model is not applicable? What is the origin of this behaviour?

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