LATE-TYPE GIANTS IN THE BULGE, AT HIGH GALACTIC LATITUDES AND IN THE PLANE

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Abstract. Mira and non-Mira M stars are easily distinguished by means of their near-infrared colours. The Miras show a large range of mass-loss rates, and the actual rates are a strong function of the K-[12] colour. The kinematics and scale heights of these Miras are a function of their pulsation periods. The period distribution of Miras in the South Galactic Cap is similar to that of Miras in the Bulge. Non-Mira M stars in the South Galactic Cap have similar colours to their counterparts in the Bulge but differ from bright M-giants in the solar neighbourhood. The galactic distribution and scale height of the M giants is a function of colour and it is suggested that differences in composition influence the colours.

1. Introduction

This paper summarizes some of the results from a survey of IRAS sources in the South Galactic Cap, selected on the basis of their IRAS 12 and 25 μm flux as high-mass-loss candidates. Details of the observations and their analysis can be found in Whitelock *et al.* (1994a,b hereafter Papers I and II, respectively).

IRAS sources with a 25 to 12 μm flux ratio of $F_{25}/F_{12} > 0.5$ were selected from galactic latitudes $b < -30°$. These criteria isolate stars with dust shells in the South Galactic Cap. Near-infrared, JHKL, photometry was obtained for all sources and repeated measurements for those with colours suggestive of something other than a normal M giant. Particular effort went into determining periods of previously unrecognized Mira variables. Spectra and optical photometry were also obtained for a significant fraction of the sample. This paper concentrates on the results for oxygen-

L. Blitz and P. Teuben (eds.), Unsolved Problems of the Milky Way, 411–417.

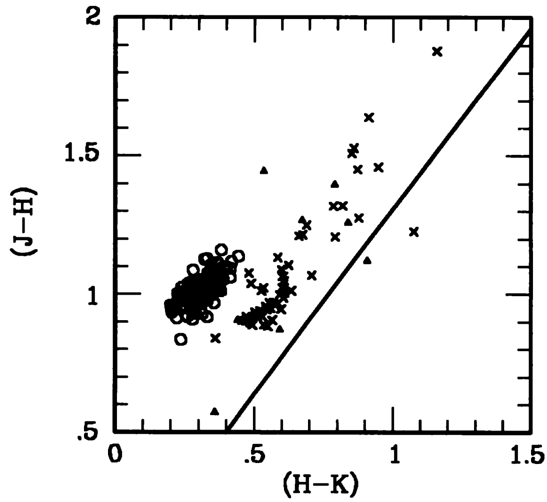

Figure 1. A near-infrared two-colour diagram of selected IRAS sources from the South Galactic Cap.

rich stars and distinguishes between Mira variables, which have pulsation amplitudes in excess of 0.4 mag at K, and non-Mira M-type giants (henceforth M giants), many of which are small amplitude variables.

Figure 1 shows the IRAS selected sample on a near-infrared two-colour diagram. The crosses are O-rich Mira variables, those higher up the diagram have thicker shells and their colours are therefore affected by circumstellar reddening. The crowded region on the left of the figure contains only the 154 M giants. The triangles represent peculiar stars which are not discussed further here. The diagram illustrates how effectively one can discriminate between Miras and other M stars on the basis of near-IR photometry alone. Our current understanding of these stars suggests that the Miras represent the last stage of Asymptotic Giant Branch (AGB) evolution for low and intermediate mass-stars. They are in the process of rapidly losing mass prior to crossing the HR diagram to become planetary nebulae. The M giants might be either on the first giant branch or on the AGB, but as they have moderately high mass-loss rates ($\gtrsim 10^{-8} M_{\odot} yr^{-1}$) most of them are probably on the AGB.

2. Mass-loss Rates

Figure 2 shows mass-loss rates for the Miras as a function of colour. These rates were calculated using a modification of the expression derived by Jura (1987) for carbon stars. This requires a knowledge of the distance, obtained from the period-luminosity relation, and the bolometric luminosity. Periods

https://doi.org/10.1017/S0074180900230003 Published online by Cambridge University Press

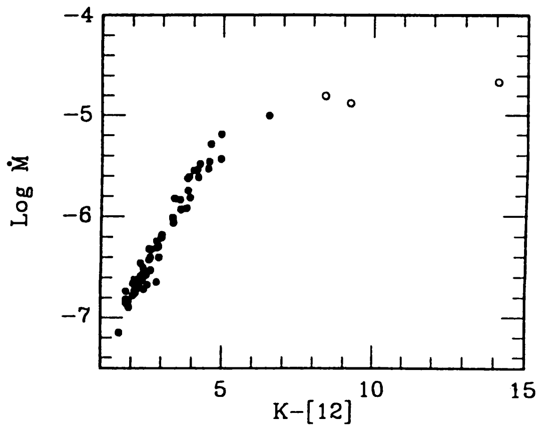

Figure 2. Mass-loss rates as a function of colour for IRAS Miras

were measured for all of the Miras, while the bolometric luminosity was derived from the combination of near-IR and IRAS photometry. As can be seen from Fig 2 the mass-loss rate is a very strong function of K-[12]. This is to be anticipated given that the 2.2 μm, K, flux originates almost exclusively from the star and the 12 μm flux from the dust. The turnover in the curve occurs where the dust becomes optically thick at 2.2 μm. The three stars with very high mass-loss rates (open circles) are carbon rich.

Assuming that the mass-loss rates for the M giants is a similar function of K-[12] then we find that the non-Miras typically have smaller mass-loss rates than do the Miras. There are, however, a few M giants with rather high rates ($\gtrsim 10^{-7} M_{\odot} yr^{-1}$). The nature of these stars was discussed in Paper II. It seems likely that they were undergoing more rapid mass-loss in the recent past than they are currently experiencing. The changed character of the mass-loss might be a consequence of helium shell flashes reducing their luminosity and forcing them out of the Mira instability strip. The remnant shell from mass-loss during the previous Mira phase is still evident in this diagram. Many of these stars may become Miras again later in their flash cycle if their luminosity rises as theory predicts.

3. Mira Pulsation Periods

The pulsation periods of the Miras are of particular interest because they are a function of the population to which the star belongs. A histogram of the periods of Miras in the South Galactic Cap was illustrated in Fig 8 of Paper I (this includes all Miras in the given volume, not just the IRAS selected sample). This can be compared with the distribution of Mira periods in various Bulge fields from Whitelock (1992 see also Glass *et al.*

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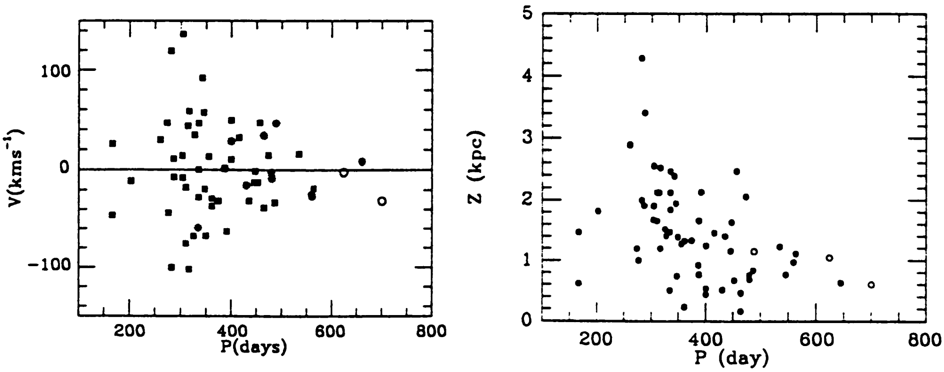

Figure 3. Radial velocity and height above the Galactic Plane as a function of pulsation period for Miras. Open-circles: carbon stars.

1994). Inclusion of the IRAS Miras extended the period distribution in the Galactic Cap towards longer periods. This distribution is very similar to that of Miras at a latitude of $b = -7^{o}.5$ in the Bulge. The innermost Bulge field, Sgr I, seems to contain a somewhat larger proportion of long-period pulsators.

We now understand that the pulsation period tells us a good deal about the star. Figure 3 shows the radial velocity and height above the galactic plane as a function of the pulsation period. Distances were calculated from the period luminosity relationship. These data reinforce what we have known since Feast's (1963) spectroscopic work; i.e., the kinematics of the Miras are a function of their pulsation period. Longer-period Miras were either initially more massive or they are younger or they are more metal rich than short period ones. One of the obvious consequences of this is that we must not visualize Miras as evolving with large changes of period, an idea that is still prevalent. It is also clear from Fig 3 that we should expect a higher proportion of short period stars in the Galactic Cap than in the solar neighbourhood purely because the bulk of the volume examined in the Cap is at large distances from the Plane.

4. Non-Mira M giants

It is of considerable interest to look at the colours of the M giants and compare them with those of similar stars in the Galactic Plane and in the Bulge. Frogel *et al.* (1990) point out that the colours of the M giants in the inner Bulge differ from those of stars in the solar neighbourhood of the same spectral type. Furthermore they find a distinct difference in the colours of the giants in the inner and outer Bulge, with those in the outer Bulge resembling globular cluster giants. It is interesting to find therefore,

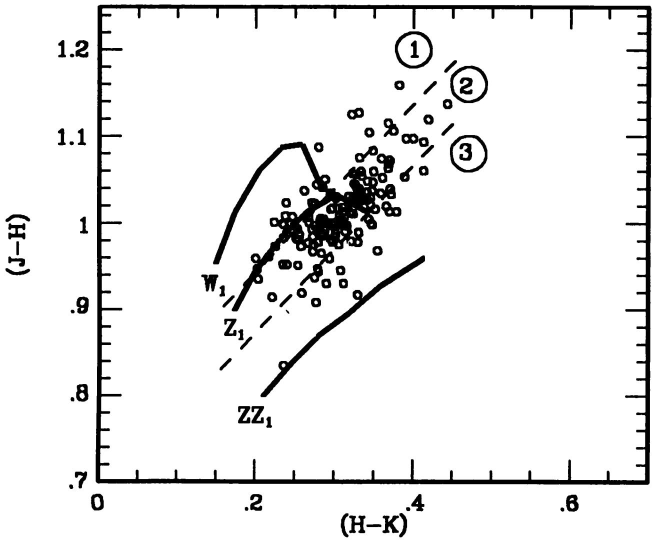

Figure 4. The M giants on a two-colour diagram; the colours have a precision of about ±0.03 mag. The solid lines are theoretical tracks from Bessell *et al.* (1989) for giants with metallicity, Z, of −0.5, 0.0 and +0.5, shifted as described by Feast *et al.* (1990). Two dashed lines divide the diagram into three parts and Table 1 lists the properties of the stars from each of these groups (see Paper II).

that the M giants from the South Galactic Cap IRAS sample have colours very similar to those of stars from the inner Bulge and quite distinct from those of stars in the solar neighbourhood or in globular clusters (Paper II). Although the colours are similar to those of the high-latitude late-M giants discovered by Stephenson (1986) and discussed by Feast *et al.* (1990) and Sharples *et al.* (1994). The critical difference between the local M stars and those from the Galactic Cap samples is probably in mass, those in the cap being less massive.

Figure 4 compares the observed colours of the M-giants with theoretical tracks. It is clear that many of the points lie outside the range of the models, so at best these models can provide only a qualitative interpretation of the data. Nevertheless, such a comparison does suggest possible reasons for the spread in the diagram. Although various factors play a role, it seems possible that metallicity is the dominant factor and that group 3 have a higher metallicity than group 2 which is higher than group 1. None of the models available allow for abundance anomalies of the type McWilliam & Rich (1994) found for K stars in the Bulge and it would clearly be important to investigate the effects on the M stars of altering abundances of α elements without changing [Fe/H].

$\Re$, (see Table 1) is the ratio of the number of stars in the hemisphere towards the Galactic Centre to the number in the opposite hemisphere.

TABLE 1. Mean properties of the M-stars from Fig 4

	Group 1	Group 2	Group 3
no. stars	27	101	26
Sp Type	5.2	5.9	7.0
J–K	1.30 ± 0.02	1.33 ± 0.01	1.30 ± 0.02
K–[12]	1.68 ± 0.13	1.47 ± 0.04	1.93 ± 0.13
V–K	6.33 ± 0.24	8.52 ± 0.88	7.31 ± 0.29
z_0 (pc)	> 500	> 330	> 560
$\Re$ ($Y < 0/Y > 0$)	0.8	1.9	4.2

Notice that stars from group 3, which has the latest mean spectral type and the highest mean mass-loss rate, are very strongly concentrated towards the Galactic Centre. For the purposes of calculating the distances to these stars, and hence the scale height, z_0, we assumed that they had the same absolute K magnitude as do stars in the Bulge with the same J–K colour. This assumption is unlikely to be correct for all of the stars in this sample and may result in an underestimate of some of the distances. However, the evidence points to these stars as having metallicities of solar or above and it is very interesting to see that they have rather large scale heights. A much deeper understanding of these stars should be possible after the completion of the DENIS and 2MASS near-infrared surveys which will provide a more complete survey of this type of star than was possible with IRAS.

Acknowledgements

I am very grateful to Michael Feast and John Menzies for helpful discussions.

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DISCUSSION

S. van den Bergh: Can one tell from presently available data if Miras belong to two distinct subsystems, or is there a gradual transition from disk to halo objects?

Whitelock: There seems to be a gradual transition from the OH/IR stars with P>1000 day in the disk to the P∼200 day Miras found in the metal-rich globular clusters.

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