MIRA VARIABLES, STELLAR EVOLUTION AND GALACTIC STRUCTURE

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1. INTRODUCTION

The Mira variables make important contributions to four of the main problems under discussion at this meeting, (1) stellar pulsation, (2) stellar evolution, (3) the morphology and history of the Galaxy, (4) the comparative study of different galaxies. The Miras also show how these rather different fields of study overlap, so that it is no longer possible to deal with any one field in isolation.

2. THE MIRAS AND STELLAR POPULATIONS

It has long been known that the Miras (defined as red giant variables of large amplitude, conventionally $\Delta V \geqslant 2.5$ mag) show, in the solar neighbourhood, both a period-asymmetrical drift and a period-velocity dispersion relation (see Table 1, data from Feast et al. 1972). The velocity dispersion perpendicular to the galactic plane (σ_W) varies from ~60 kms^{-1} at 200 day period to ~26 kms^{-1} at 400 day period, corresponding to scale heights of about 1000pc and 300pc respectively. Table 1 shows that if we adopt a velocity of the sun in the direction

Table 1

Asymmetrical drift with respect to sun (V) and total velocity dispersion (σ_T) for Miras and local M giants

(a) Miras

Range of Periods (days)	Mean Period (days)	V kms^{-1}	σ_T kms^{-1}	No. of stars
<140	131	-33 ± 13	81	22
145-200	179	-111 ± 22	180	46
200-250	225	- 61 ± 9	101	71
250-300	270	- 33 ± 10	88	77
300-350	324	- 32 ± 6	69	83
350-410	382	- 23 ± 8	58	54
>410	454	- 15 ± 8	50	35

(b) local M giants

-	-	- 18.3	42	266

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of galactic rotation of $-13\ \mathrm{kms}^{-1}$ relative to the circular velocity then Miras with periods between 145 and 200 days ($\bar{P}$ = 179 days) have an asymmetrical drift of $98 \pm 22\ \mathrm{kms}^{-1}$, distinctly less than that of halo objects (e.g. $220 \pm 23\ \mathrm{kms}^{-1}$ derived by Oort (1965) for RR Lyrae variables with $\Delta\delta > 5$) but greater than that of Gilmore's thick disk (~30 kms^{-1}, Sandage 1987, Gilmore this volume). Presumably indicating the existence of objects of age intermediate between that of the halo and that of the thick disk. Miras with periods of ~250 days have kinematics similar to that of the thick disk.

A number of Zinn's (1985) disk globular clusters contain Mira variables. Their periods range from 191 days (NGC 6712) to 265 days (NGC 6553), and possibly to 310 days (NGC 5927) (cf. Feast 1981). Over this period range the kinematics of the local Miras change rapidly with period (cf. Table 1 and Feast et al. 1972 Fig.2) and this suggests that there is a range of kinematic subgroups amongst the disk globular clusters. The recent analysis of Armandroff (1988) would also lead to this same conclusion. He finds an asymmetrical drift of ~30 kms^{-1} for the disk globular clusters as a group (a considerable revision from earlier estimates). However the results just discussed strongly suggest that clusters containing Miras of ~200 day period (47 Tuc, NGC 6712, 6637, 6356) must belong to a population with a distinctly larger drift (~70 kms^{-1}).

3. MIRAS, SEMIREGULARS, STELLAR EVOLUTION AND STELLAR PULSATION

In any globular cluster with more than one Mira variable, the periods are all close to one another and the mean period tends to increase with the cluster metallicity (cf. Feast 1981). The Miras are also bolometrically the most luminous stars in such a cluster and evidently mark the end of AGB evolution. The kinematic results of the last section indicate that the period of a Mira is a function of its age and hence of its initial mass and/or metallicity. From these results it is possible to infer initial masses ranging from about $0.9M_{\odot}$ at a period of 200 days to about $1.1M_{\odot}$ at a period of 400 days with some dependence of the masses on the adopted metallicity (cf. Feast and Whitelock 1987).

The Mira variables in the Large Magellanic Cloud have a well defined Period-Luminosity (PL) relation. The relation at K(2.2μm) for M and S type stars has a remarkably small scatter (σ = 0.13 mag). This is an upper limit since there are still not good infrared light curves for all the stars. Work is in progress to see whether the true width of the relation can be established. Bolometric luminosities (from integrated JHKL fluxes) are somewhat less well determined but there is still an excellent PL relation (σ = 0.16 mag) (Glass et al. 1987). The dependence of kinematics on period for Miras in the solar neighbourhood shows that the Mira PL relation is not an evolutionary sequence but the locus of the end points of AGB evolution of stars of different masses and metallicities. This is further demonstrated by the data on bolometric luminosities of Miras and of smaller amplitude semiregular red variables in globular clusters, assembled and discussed

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by Whitelock (1986). The data for metal rich clusters show that this subset of semiregular variables define a line in the PL diagram (Fig.1) of shallower slope than the Mira PL relation. This shallower line is evidently an evolutionary track along which a star either evolves from short to long period or perhaps oscillates back and forwards over all or part of its length as it undergoes thermal pulsing. We might expect semiregular variables of different mass/metallicities to lie on tracks roughly parallel to that defined by the metal rich clusters.

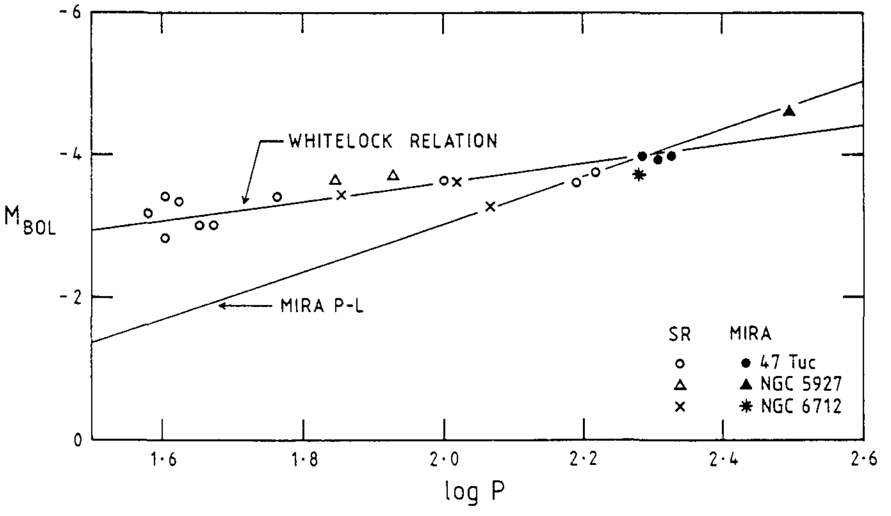

Fig.1. The low amplitude semiregular variables and Miras in metal rich globular clusters (from Whitelock 1986). The Mira PL relation is also shown.

Whitelock's work has revealed another interesting result. If one plots semiregular variables from metal poor and metal rich clusters on the same PL diagram (e.g. Whitelock 1986 Fig.2) one finds that they define roughly the same line. If the cluster distances are derived using a constant horizontal branch luminosity at all metallicities then the variables in metal poor clusters are slightly less luminous at a given period than those in metal rich clusters. If the absolute magnitudes of the horizontal branches are taken as, constant +0.2 [Fe/H], (a relation for which there is some support, see summaries in Feast 1988, Sandage this volume) then the metal rich and metal poor variables lie rather close to the same line. These possible changes are not important for the present purpose since they leave any difference in luminosity between metal poor and metal rich variables small at a given period. Whitelock also finds that in a plot of log P against log T (where T is the temperature derived from infrared photometry) there is a rather clear separation between metal rich and metal poor variables, amounting to Δ log T ~ 0.1 at a given period (see Whitelock 1986 Fig.3). It is very unlikely that errors in the calibration of log T can be sufficient to account for this difference. In fact, as White-

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lock points out, an error in log T can hardly explain this result for the following reason. The variables fall on or close to the giant branches of the clusters in which they lie. Since the luminosities of the two groups of variables are the same, or nearly the same, at a given period, making the log T values also the same would force together the giant branches of different metallicities in the HR diagram. However a metallicity dependent separation of these branches is expected theoretically and observationally confirmed (e.g. Frogel et al. 1983). It must therefore be concluded that there is a real separation of the two groups in the period - log T plot. The pulsation equation,
$\log Q = 0.5 \log M + \log P + 0.3 M_{bol} + 3 \log T - 12.71$,
then shows that this result implies a difference in mass (M) or pulsation constant (Q) (or both) between the two groups. To explain the result in terms of a mass difference would require the masses of the metal rich variables to be a factor four greater than the masses of the metal poor ones. So large a difference seems quite unlikely. Whitelock points out that a change of Q by a factor of two will produce the desired result. This implies that the small amplitude metal poor variables pulsate in the fundamental mode and the metal rich ones in the first overtone.

4. MIRAS IN DIFFERENT SYSTEMS

It is useful to compare the Miras in the LMC, SMC, globular clusters and the galactic bulge. The LMC Miras show a narrow PL relation at K even when carbon Miras are included. The LMC data give the best determined slope and the Mira data in the other systems can be compared with it. The relatively small amount of data in the SMC (mainly from Lloyd Evans et al. 1988) yields, within the errors, a PL relation of the same slope as the LMC and, equally important, the same zero point (Feast 1988). The range in periods of Miras in globular clusters is not large enough to get a particularly accurate value for the slope, but within the uncertainties, the LMC slope fits the cluster data. This is true whether one uses a cluster distance scale based on a fixed horizontal branch luminosity or on one depending on [Fe/H] (cf. Menzies & Whitelock 1985, Feast, 1984, Feast 1987). In several of these discussions the 149 day variable in ω Cen is found to lie below the mean relation by ~0.3 mag. This variable will no longer be so discrepant if one adopts the revised (increased) distance modulus for this cluster discussed by Dickens (this volume). The Miras in the galactic bulge (the NGC 6522 window) observed by Glass & Feast (1982) and Wood et al. (1985) also show a PL relation of the same slope as the LMC variables (Feast 1986). The bulge stars show a considerable scatter about this relation due to the spread of the stars along the line of sight. A comparison of the Mira PL zero points in the LMC, the globular clusters and the galactic bulge depends to some extent on whether RR Lyrae variables (or horizontal branches) have luminosities which depend on [Fe/H] or not. Within the uncertainties introduced by this situation there are no evident zero point discrepancies (cf. Feast 1987, 1988).

5. MIRAS, IRAS SOURCES AND THE AGE OF THE GALACTIC BULGE

This topic has been reviewed several times recently (Feast 1986, Feast & Whitelock 1987, Feast 1987) and only a brief summary is given here. Optical Miras in the bulge (the Baade Windows) have periods ranging up to 400-500 days (Lloyd Evans 1976). These periods correspond (Feast & Whitelock 1987) to initial masses of about $1.1M_{\odot}$ and ages of about 5 Gyr or greater (depending on the metallicity). Are there evolved stars in the bulge which are younger, or have higher initial masses, than this?

In the Galactic disk generally we find objects which apparently extend the optical Mira sequence to longer periods. These are the OH/IR stars with periods of 800 to 2000 days. It has been suggested that these OH/IR stars extend the Mira PL relation to longer periods (Feast 1985). Independent of this, any OH/IR star with M_{Bol} in the range -5.4 to -6.3 (the expected range on the PL relation, for 800 to 2000 day variables) will have higher initial mass (about 1.5 to 2.5 $M_{\odot}$) and younger ages than the optical Miras (cf. Iben & Renzini 1983 Fig.7, Feast & Whitelock 1987). Since such objects are dust enshrouded they are likely to have been missed in optical searches of the bulge. The IRAS survey provides an excellent opportunity to discover whether or not bright, long period OH/IR stars are present in the bulge. It was quickly realized that most IRAS sources in the bulge were Miras or at least Mira-like (Habing 1986, Feast 1986). In the Baade windows most of the IRAS sources are known optical Miras (Feast 1986, Glass 1986). This latter result suggests that the relative number of IRAS Mira-type objects in the bulge with period greater than 500 days must be small. This conclusion is strengthened by a ground-based JHKL survey of IRAS sources in a strip at $|b|$ between 7° and 8° (b = galactic latitude) being carried out by Whitelock, Catchpole and Feast (see Whitelock, Feast & Catchpole 1986, Feast & Whitelock 1987). These results suggest that there are relatively few Mira-like objects with M_{Bol} brighter than -4.7 which, on the PL relation, corresponds to a period of about 400 days. Harmon & Gilmore (1987) have carried out a statistical analysis of data from the IRAS survey. Making certain simplifying assumptions they suggest that there may be a significant fraction of the bulge (IR) Miras with periods greater than 600 days. If this is so it may put the upper limit to the initial masses of bulge stars slightly higher than the value derived above ($1.1M_{\odot}$). Work is in progress to determine the periods of a significant sample of IRAS bulge sources so as to place firmer upper limits on the initial masses.

The above discussion refers to the bulge region in general. Some years ago an OH survey (Winnberg *et al*. 1985) revealed a population of OH/IR stars within $0\overset{\circ}{.}3$ of the galactic centre. These objects seem distinctly more luminous than the Mira-like objects found further out in the bulge. The data of Jones & Hyland (1986) (cf. Feast 1987) yield a mean M_{Bol} of about -5.4 for these objects corresponding to a mean initial mass of about $1.5M_{\odot}$. Further observation are required to investigate the possibility of a range in masses for these objects. More recent OH surveys (Winnberg 1988) over a wider area reveal many more objects which seem likely to be of the same type. They are found

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to be strongly concentrated to the galactic plane. Possibly these objects are best regarded as belonging to the inner part of the galactic disk rather than the bulge proper.

6. POST-MIRA EVOLUTION

If Miras lie at the tip of the AGB, they are expected to evolve rapidly into planetary nebulae (PN). Thus to a first approximation we expect the mass of the PN envelope to be equal to the difference between the (pulsation) mass of the Mira and the final (white dwarf) mass. Observations and theory (Weidemann 1984, Mazzitelli and D'Antona 1986) indicate that the final white dwarf mass varies rather little with initial mass. It is perhaps as low as $0.55M_{\odot}$ for an initial mass of $0.9M_{\odot}$ but generally lies close to $0.65M_{\odot}$ out to initial masses of about $5M_{\odot}$. Thus the mass of the PN envelope will increase quite rapidly with increasing initial mass. Data compiled from various sources by Pottasch (1988a) show that the mass of ionized gas in a PN envelope has an upper limit (in the available data) of $\sim 1M_{\odot}$ for PN in the solar neighbourhood and in the Magellanic Clouds. This ionized mass is obviously a minimum value for the upper limit to the total envelope mass and implied stellar masses at the Mira stage of at least $1.7M_{\odot}$.

PN in the galactic bulge provide an interesting confirmation of this general picture of post-Mira evolution. Both radio (Gauthier et al. 1983) and optical (Kinman et al. 1988) surveys of bulge PN show that there is an upper limit of close to $0.3M_{\odot}$ for the ionized mass in the envelopes of these objects. In the case of the optical sample of Kinman et al., Pottasch (1988b) has shown that if one assumes the envelopes are optically thick then the central stars of these objects must lie in a region of the HR diagram well away from the expected evolutionary tracks for these objects. It would seem best to interpret this result as indicating that these objects are not optically thick. In that case the ionized mass is equal to the total mass in the envelope and we deduce an upper limit to the total mass of $0.3M_{\odot}$. As indicated above the masses of some PN envelopes in other regions can be higher than this. This shows that the upper range of PN progenitor masses is missing in the galactic bulge. This is of course what was found in section 5 (an upper limit of $\sim 1.1M_{\odot}$ for the initial masses of bulge objects). There is in fact good quantitative agreement with predictions. A combination of pulsation masses of Miras and evolutionary theory (Feast & Whitelock 1987) predicts that an object of initial mass $1.1M_{\odot}$ will yield a PN envelope of $\sim 0.3M_{\odot}$.

Recently, Webster (1988) has published an important study of line intensities and abundances for PN in the bulge. She suggests that a few of these objects may qualify for classification as Type I PN (PN with high helium and nitrogen abundances). It seems likely (cf. Peimbert & Torres-Peimbert 1983) that at least some Type I PN evolve from massive objects (initial masses of $2\text{-}5M_{\odot}$). In the light of the previous discussion, and also the work of Terndrup (1988) on the main sequence turn-off in the bulge, it seems unlikely that there can be objects with

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initial masses as large as 2-5$M_\odot$ in the bulge. Further work is desirable to establish whether Webster's candidates are indeed of type I and also to place the mass determination of Type I PN on a firmer basis. It would obviously be of interest to derive the envelope masses for the bulge Type I PN candidates.

7. POSSIBLE MIRA PROGENITORS

Since short period (~200 day) Miras occur in metal rich globular clusters, the immediate progenitors of such Miras must be stars (small amplitude variables and constant stars) like those on the upper part of the AGB in these clusters. It has not however been possible to identify so easily the immediate progenitors of the longer period Miras. The galactic bulge with its large population of Miras of all periods might well be expected to yield important clues to these progenitors. The large number of M giants present in the bulge (e.g. Blanco et al. 1984) suggests these as candidate progenitors. In the past it was not possible to identify these stars as Mira progenitors because their surface distribution across the bulge (Blanco & Blanco 1986) seemed quite different from that of the Miras (cf. Feast 1987 esp. Table 7). However Blanco (1987) has considerably revised this derived surface distribution and the results are now quite similar to that of the Miras and of some other bulge objects (cf. Table 2). It would now seem reasonable to believe that these bulge M giants are progenitors of at least the longer period bulge Miras.

If this is the case we are left searching for the progenitors (presumably M giants) of the longer period Miras in the solar neighbourhood. Frogel & Whitford (1987) have emphasised that the Blanco et al. M giants in the bulge are different (e.g. in infrared colour-spectral type relations) from a sample of bright M giants in the solar neighbourhood. However it seems unlikely that these latter stars can, as a group, be considered the progenitors of the Miras in the solar neighbourhood. The kinematics of solar neighbourhood M giants is different from that of Miras. This is illustrated in Table 1 where it will be seen that the total velocity dispersion (σ_T) of the local M giants (cf. Delhaye 1965, Parenago 1951) is less than that of any of the Mira groups quoted in the table and that the group motion of the M stars with respect to the sun in the direction of galactic rotation is distinctly different from all but the two longest period groups of Miras. It seems likely that the bright local M giants are younger, more massive stars than is required for the Mira progenitors.

TABLE 2

Ratio of the number of Objects per unit area in the Bulge Window at $\ell = 1^\circ$ $b = -3^\circ.9$ (NGC 6522 field) to that at $\ell = 0^\circ$ $b = -8^\circ.5$ (Plaut field 3)

Optical Miras	=	10
IRAS Sources	=	13
RR Lyrae variables	=	17
Late M type stars	=	12

In these circumstances the most promising candidates for the progenitors of local long period Miras are the late M stars identified by Stephenson (1986) in a survey of a region at galactic latitudes greater than 10° (or perhaps a subset of these late M stars). Investigations are in progress by a group at SAAO to see how these stars are related to the local Mira population and to the M giants in the galactic bulge.

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