

A Galactic Bar to Beyond the Solar Circle and its Relevance for Microlensing

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Abstract. The Galactic kinematics of Mira variables have been studied using infrared photometry, radial velocities, and Hipparcos parallaxes and proper motions. For Miras in the period range 145 to 200 days (probably corresponding to $[\text{Fe}/\text{H}]$ in the range -0.8 to -1.3) the major axes of the stellar orbits are concentrated in the first quadrant of Galactic longitude. This is interpreted as a continuation of the bar-like structure of the Galactic Bulge out to the solar circle and beyond.

1. Introduction

A somewhat unexpected discovery of microlensing experiments towards the Galactic Bulge was the need to take into account a bar-like structure there (see, e.g. Paczyński 1996). The precise nature of this bar - its composition, extent and evolution - is only sketchily known. This is an area where progress is likely to come from the combination of microlensing results with other types of observations. In the present paper we summarize the results of an analysis of the Galactic kinematics of Mira variables based on infrared photometry, radial velocities, and Hipparcos parallaxes and proper motions (Whitelock, Feast & Marang 2000, Whitelock & Feast 2000, Feast & Whitelock 2000b). This provides evidence for a rather extended bar-like structure in the Galaxy.

2. Background

Mira variables have a number of properties which makes them particularly interesting for Galactic structure studies ¹.

Bolometrically and in the near infrared, e.g. at K ($2.2\mu\text{m}$), they are the brightest members of the old populations in which they are found (see for instance fig 1 of Feast & Whitelock 1987). These variables therefore define the

¹Note that the present paper refers entirely to oxygen-rich Miras.

tip of the AGB in these populations. Because of their brightness they can be studied with relative ease to large distances.

Observations in the LMC show that Miras follow a well defined, narrow period - luminosity (PL) relation at K or in M_{bol} (Feast et al. 1989). Thus Mira distances can be estimated from infrared photometry with good accuracy.

It has long been known that the kinematics of Galactic Miras are a function of period (see, e.g. fig 12 of Feast 1963). Their asymmetric drift gets numerically larger as one moves from the longer period Miras to the shorter period ones with a maximum of $\sim 100 \text{ km s}^{-1}$ at a period of about 175 days. This is intermediate between the value usually quoted for the thick disc ($30 - 40 \text{ km s}^{-1}$, e.g. Freeman 1987) and that appropriate to halo objects ($\sim 230 \text{ km s}^{-1}$). This apparently intermediate population has generally been neglected in discussions of Galactic structure and kinematics. Judging from Miras in globular clusters this corresponds to a metallicity, $[\text{Fe}/\text{H}]$, range from about -0.8 to about -1.3 . As one moves to Miras of even shorter periods the numerical value of the asymmetric drift decreases, making the shortest period Miras similar in kinematics to Miras of much longer period. The relationship of this shortest period group to the other Miras was long a puzzle.

Another important property of the Miras is shown by those in globular clusters. Miras occur in relatively metal rich clusters. If there are more than one Mira in any cluster, their periods are all close together. Such clusters also contain semiregular (SR) variables. In any one cluster these have a range in periods, and in the period - luminosity plane they lie on an evolutionary track which terminates on the Mira PL relation (see Whitelock 1986, Feast 1989). The clusters containing Miras show that for these stars there is a good relation between period and metallicity (see fig 1 of Feast & Whitelock 2000a). Since the change of mass with metallicity is presumably small for these stars, the period - metallicity relation is primarily indicating a relation between metallicity and stellar radius at the tip of the AGB.

These various properties have been important in using Miras to study the Galactic Bulge itself. The work of Lloyd Evans (1976) and others showed that there was a wide distribution of periods amongst Miras in the Bulge. This, then, implies a wide range in metallicities. Indeed the metallicity distribution inferred from the Mira period distribution (Feast & Whitelock 2000a) is similar to that derived by Sadler et al. (1996) from Bulge K-type giants. The PL relation allows one to estimate the distances to individual stars in the Bulge (see, e.g. Glass et al. 1995). In this way Whitelock & Catchpole (1992) found that Bulge Miras at positive Galactic longitudes were nearer to us than those at negative longitudes. This was one of the first pieces of evidence for a barred structure of the Bulge.

3. Present Work

Our present study consists of extensive near infrared, $JHKL$, photometry of Galactic Mira-like variables², made at SAAO Sutherland, combined with Hip-

²The sample contains a few stars classified as semiregular (SR) variables which have Mira-like properties (see Whitelock et al. 2000).

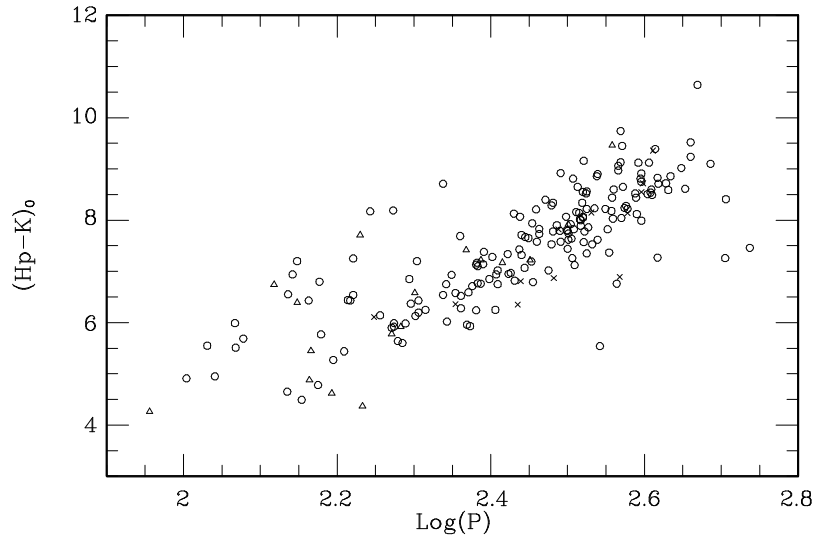


Figure 1. The period-colour relation for oxygen-rich Mira-like variables. Stars catalogued as Miras and semi-regulars are shown as circles and triangles, respectively. S-type stars are shown as crosses

parcos astrometric and photometric data and with radial velocities from the literature.

Combining the infrared observations with the Hipparcos photometry allows us to see clearly the cause of the anomalous result for the asymmetric drift of the shortest period Miras discussed above. In the $(Hp - K)_0 - \log P$ plane (where Hp is the mean Hipparcos magnitude) there are two near parallel sequences (see Fig 1). A main (blue) sequence and a less populated, redder, sequence which is largely confined to the shorter periods and dominates at the very shortest periods. In the period range where the two sequences overlap their kinematics are quite different. The red sequence stars have kinematics which associates them with much longer period Miras. It is tempting therefore to identify some at least of the stars on this red sequence as analogous to the SRs in metal-rich globular clusters, which were discussed above, but at somewhat higher luminosities, and to suggest that they are evolving into longer period Miras. If this is the case we would expect the red sequence stars to be somewhat brighter than the blue sequence ones at a given period. This is because evolutionary tracks (at least in metal-rich globular clusters) lie above the Mira PL relation in the period - luminosity plane. Indeed the Hipparcos parallaxes do indicate that at a given period the red sequence stars are brighter than the blue sequence ones. It is also possible that some of the red sequence stars are pulsating in a higher mode than the blue sequence stars. The following discussion refers only to the main (blue) sequence stars. These stars may also be recognized from their infrared colours and these show that the Miras that have been found in globular clusters and the LMC belong to the blue sequence.

Hipparcos parallaxes of blue sequence stars were used to derive the zero-point of the PL relation. Using this calibration one can determine a distance modulus for the LMC. This is found to be 18.64 ± 0.14 mag or slightly greater if

a correction is necessary for a metallicity difference between the local and LMC Miras. This modulus agrees well with that determined from Cepheids and some other distance indicators (see the summary in Feast 1999).

We have studied the Galactic kinematics of the blue sequence Miras using Hipparcos proper motions and radial velocities from the literature. These radial velocities include radio observations of OH and other molecules. Distances were derived from the mean K magnitudes and the Hipparcos calibrated Mira PL relation. However, the results are rather insensitive to the distance scale adopted.

The three components of the space motion of each star were derived in non-rotating cylindrical co-ordinates centred at the Galactic centre. These are V_R radially outwards and parallel to the plane, V_θ at right angles to V_R in the direction of Galactic rotation, and w in the direction of the North Galactic Pole. The data were analysed by dividing the Miras into six (blue sequence) groups, according to period.

The results for V_θ confirm previous work. In the longest period group (mean period 453 days), $V_\theta = 223 \pm 4 \text{ km s}^{-1}$. This is only slightly smaller than the circular velocity implied by the kinematics of Cepheids (231 km s^{-1} , Feast & Whitelock 1997). The value of V_θ drops as the period decreases reaching $147 \pm 14 \text{ km s}^{-1}$ in the group of mean period 175 days (17 stars). In this calculation one Mira in the period range 145 to 200 days (S Car) has been omitted, as it is moving on a highly eccentric retrograde orbit.

The main surprise of the analysis was in the values of V_R . This is $+67 \pm 17 \text{ km s}^{-1}$ in the group of mean period 175 days, whilst for the other groups there is a small net outward velocity.

There seem to be three possible explanations of this large mean outward radial motion in the 145 to 200 day group.

If the Galaxy is axially symmetric the result would imply that there is a general, axially symmetric, outward, radial motion of Miras in the period range 145 - 200 days. This seems unlikely.

Another alternative is that Miras in this period range belong to some galactic interloper. Whilst this cannot be ruled out we might ask why there are, in that case, no local stars of this type belonging to our Galaxy (such stars exist in the Galactic Bulge itself and in Galactic globular clusters). Also the mean motion perpendicular to the plane is small for this period group ($w = -12 \pm 12 \text{ km s}^{-1}$) indicating that any interloper must be moving very closely parallel to the Galactic plane.

The most likely explanation would seem to be that there is a Galactic asymmetry leading to a deficit of incoming orbits in the solar neighbourhood for Miras in this period range. The values of V_θ and V_R for this group then show that the major axes of their Galactic orbits are concentrated in the first quadrant of galactic longitude. All workers place the major axis of the Bulge-bar in this quadrant. A simple first-order calculation shows that the mean orbit has a major axis making an angle of 17_{-4}^{+11} degrees with the Sun - Centre line. This agrees with the position angle of the Bulge-bar derived by Binney et al. (1991) from gas dynamics in the central region (16 degrees). It would be consistent with a number of other estimates which are in the 20 to 30 degree range, though values near 45 degrees derived by some workers agree less well.

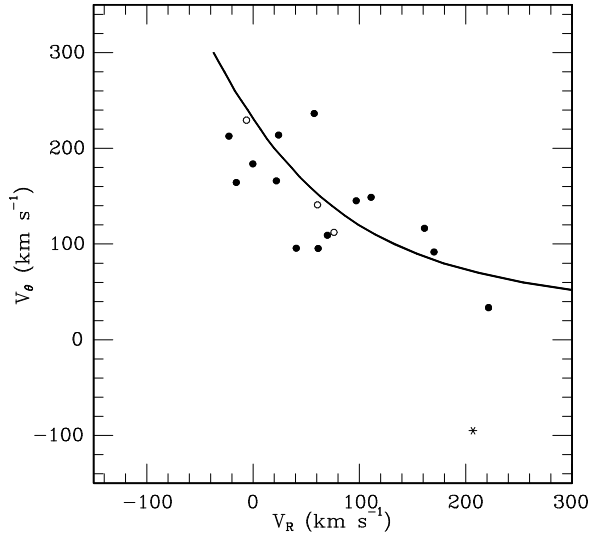


Figure 2. A plot of V_θ against V_R for stars with periods in the range 145 to 200 days. The curve is the relation expected on a simple model in which the major axes of the orbits of all the stars are aligned at 17° to the Sun-Centre line. Stars for which any velocity component has a standard error in excess of 20 km s^{-1} are represented by open symbols. The asterisk denotes S Car.

Rough estimates suggest that the orbits of some of these short period Miras are sufficiently eccentric to penetrate into the Bulge region itself at perigalacticum.

Figure 2 shows a plot of V_θ against V_R for stars in the 145 to 200 day group. The curve is the relation that would be expected, on a simple model, if the major axes of the orbits of all the stars were aligned at an angle of 17 degrees to the Sun - Centre line.

The number of Miras in the short period group is small, 17 stars (omitting S Car for reasons mentioned above). However, the lifetime of a Mira is short ($\sim 2 \times 10^5$ years). Thus these stars are tracers of a much larger population. This can be seen from the metal-rich globular clusters, where one such cluster may contain just one Mira. It would be particularly interesting to identify other objects associated with the 145 to 200 day Miras. The globular cluster results suggest that such objects would have metallicities in the range $-0.8 \geq [Fe/H] \geq -1.3$ and the age of globular clusters in this metallicity range. However, the situation may be complex. Minniti et al. (1997) suggest that the RR Lyrae variables in the Bulge do not belong to a bar-like distribution, despite the fact that the ones in the NGC 6522 field, at least, have $[Fe/H] \simeq -1$ (Walker & Terndrup 1991). It may be that choosing Miras by period allows one to sort out a more homogeneous population than is possible in other ways.

So far as microlensing is concerned this work would seem relevant for at least two reasons.

1. It gives hope of defining further the composition and general character of the Galactic bar.

2. It warns that one should not necessarily consider Galactic structure and kinematics as “knowns” into which microlensing studies must be fitted. There may well be surprises; and microlensing data may make an important contribution to uncovering them.

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