Mirases and Other Cool Variables with GAIA

Michael Feast  
_Astronomy Department, University of Cape Town, Rondebosch, 7701, South Africa_  
muf@artemisia.ast.uct.ac.za

Abstract. A general review is given of Miras and some other cool variables stars, concentrating on those aspects on which GAIA, and more particularly GAIA spectroscopy and radial velocities, will have a major impact.

1. Introduction

The observation of Miras and other late type variables with GAIA will bring rather special rewards, but it will also bring special problems in analysing and interpreting the data. In reviewing some of these promises and problems I hope it will become clear what a vital part in the success of the mission will be played by the spectroscopy; radial velocities and spectral data. I shall also mention ground based observations which will be need to make full use of GAIA data.

Mirases are large amplitude, AGB variables with rather regular periods which range from about 100 days to 1000 days or more. At the longer periods they are often OH/IR sources. They can be broadly divided into oxygen-rich and carbon-rich objects (O- and C- Miras).

It has been estimated (Eyers & Cuypers 2000) that GAIA will discover and measure about 150,000 Mira variables. For a significant fraction of these, GAIA will obtain parallaxes, proper motions, radial velocities, spectral data, narrow and broad band photometry and periods. For many of the stars observations will cover the whole light cycle.

Mirases are of central importance to a number of key issues in astronomy. Amongst these are the following. (1) They appear to define the end point of the AGB when mass-loss plays a major role in stellar evolution. This is a time in the life of a star which is not properly understood. (2) In old or intermediate age populations, the Miras are the brightest individual stars and hold out the possibility of calibrating the populations of nearby galaxies in which they can be isolated and studied. (3) They show a well defined period-luminosity relation making them important galactic and extragalactic distance indicators. (4) Mira periods are related to age and/or metallicity. They are therefore important traces of galactic structure and kinematics.
2. The O-Miras

Consider first the O-Miras. In the LMC these variables show a narrow period-luminosity relation in the infrared. At K (2.2 microns) the scatter about this relation is only 0.13mag (Feast et al. 1989). So far as we have been able to tell the slope of this relation is the same everywhere (i.e. in the SMC, in globular clusters and for Miras with individual distances from proper motion companions, Whitelock et al. 1994, Wood 1995, Feast and Whitelock 1999, Feast, Whitelock & Menzies 2002). Hipparcos allowed the zero-point of this relation to be calibrated directly from Mira parallaxes (Whitelock & Feast 2000a) and also indirectly through Miras in globular clusters with distances based on Hipparcos subdwarf parallaxes (Feast et al. 2002). GAIA will allow one to study this relation in great detail in the galactic field, provided the necessary ground-based infrared observations have been made (a programme along these lines has been started at the South African Astronomical Observatory by P.A. Whitelock, F. Marang and the writer). For the Miras with good coverage of the light curve by GAIA it will also be possible to discover whether one can replace the infrared photometry with some of the GAIA photometry. It may be that the GAIA photometry, together possibly with the spectra, will show evidence for a period-luminosity-colour relation of which there was a hint in the infrared photometry (Feast et al. 1989).

The galactic kinematics of O-Miras are particularly interesting and Hipparcos led to some unexpected results. It has long been known that the galactic kinematics of O-Miras are a function of period (e.g. Feast 1963) and this allows the galactic kinematics of old and intermediate age stars to be studied as a function of age and/or metallicity in finer detail than is possible in other ways. Hipparcos improved this discussion in three ways. (1) The Hipparcos calibration of the PL(K) relation, mentioned above, allowed one to obtain the distances of many local Miras. (2) The Hipparcos proper motions could then be used together with (ground-based) radial velocities to obtain space motions (Feast & Whitelock 2000a). Full space motions are essential if we are to study galactic kinematics free of assumptions. (3) The Hipparcos photometry together with ground-based infrared photometry showed that the short period O-Miras divided into two groups with different mean colours at the same period (Whitelock, Marang & Feast 2000, Whitelock 2002). These two sequences were called the short-period (SP) -red and -blue groups. These two groups differ in their kinematic properties and it will be essential in any future work to distinguish between them. In the case of GAIA observations, this may perhaps be done spectroscopically since the SP-red stars have a later mean spectral type than the SP-blues at a given period. It may also perhaps be possible using the GAIA photometry. On the basis of infrared colours alone which show the division into two groups, though less clearly, and on the basis of kinematics one can show that Miras in globular clusters belong to the SP-blue group which, together with longer period Miras, can be called the main Mira sequence. These Miras in clusters, and by implication the Miras in the main Mira sequence generally, lie at the tip of the AGB and are the brightest objects, bolometrically, of their populations.

What of the SP-red Miras? They have different colours, spectral types and kinematics from the SP-blue Miras (see Whitelock et al 2000 and Feast &
Whitelock 2000a for details). Their kinematics associate them with longer period Miras on the main Mira sequence. At present the best guess is that they are not yet at the end of their AGB lives but will evolve into Miras of longer period on the Mira main sequence. There is some evidence (Whitelock and Feast 2000a) that at a given period the SP-red Miras are brighter than the SP-blues. This would be consistent with the above discussion. Clearly we can anticipate that GAIA will clarify this whole picture using its combination of parallaxes, proper motions, radial velocities, spectral types and photometry. This will be a considerable contribution both to our understanding of AGB evolution and to the study of Our Own and other galaxies.

When the SP-red stars are omitted, the rest (i.e. the main Miras sequence, including the SP-blue variables), show a monotonic dependence of kinematics on period. In particular, the space motions show a smooth change in $V_\theta$ (the velocity in the direction of galactic rotation) from $133 \pm 19$ km s$^{-1}$ at a mean period of 173 days to $223 \pm 4$ km s$^{-1}$ at a period of 453 days (see Feast & Whitelock 2000a and Feast 2002). This is for stars which are mostly within about 1 kpc of the Sun. This dependence opens up the possibility of studying galactic kinematics of homogeneous populations of old and intermediate age stars on a much finer grid than is otherwise possible. Some guidance as to the nature of this grid is provided by Miras in globular clusters. These are confined to the more metal-rich clusters and to the shorter period Miras. In addition there is a rather clear period-metallicity relation for Miras in clusters (see Feast and Whitelock 2000b).

To understand this relation we need to know whether the initial masses of the Miras in clusters (i.e. the turn-off masses) are a function of metallicity. This in turn requires us to know whether all the metal-rich globulars are the same age or whether age depends on metallicity. GAIA will make a major contribution to settling this issue by providing much improved estimates of globular cluster distances, either directly or through subdwarf parallaxes. However it seems worth noting that this will probably also depend on there being much more detailed ground-based spectroscopic work to determine chemical abundances in subwarfs both in the field and in clusters.

Apart from the globular cluster Miras there is rather little direct evidence on the initial masses of Miras. R Hya is a member of the Hyades moving group (Eggen 1985) and this suggests an initial mass of $\sim 2M_\odot$. However this Mira is unusual, its period having varied from about 500 days to 385 days in the last 340 years (see e.g. Zijlstra, Bedding & Mattei 2002), probably due to the star being in a shell-flashing stage (see below). General arguments based on galactic kinematics and scale heights (e.g. Olivier, Whitelock & Marang 2001) suggest masses of $\sim 2M_\odot$ for Miras with periods in the range $\sim 400$ to 800 days and $\geq 4M_\odot$ for periods of $\geq 1000$ days. In the Magellanic Clouds (Nishida et al. 2000) there are intermediate age clusters with turn-off masses of $\sim 1.5M_\odot$ which contain C-Miras of period $\sim 500$ days. It may very well be that C- and O-Miras of the same period have the same initial masses but this has not yet been definitely established. We can expect GAIA to make an important contribution to the mass question. For instance the space motions from GAIA should allow the isolation of new moving groups some of which may contain Miras. We already know of a few Miras with common proper motion companions. Such objects are potentially important for the determination of limits to the initial mass of the Mira as well as its luminosity and, importantly, its chemical composition.
which is difficult to derive directly for a Mira in view of its cool and complex atmosphere. Incidentally, it is not clear that the Hipparcos catalogue has been properly searched yet for Miras with proper motion companions.

The dependence of the mean motion of Miras in the direction of galactic rotation ($V_\theta$) on period shows their importance for problems of galactic structure and dynamics. A quite unexpected result was found from the motion of Miras radially outwards from the galactic centre ($V_R$). Dividing the Miras into groups according to period, it was found that for Miras in the groups with mean periods of 228 days or more there is a small net outward motion of a few km s$^{-1}$. The significance of this is not at present very clear. However a rather startling result was found for the shortest period group (mean period 173 days) when the SP-red variables were omitted. These stars show a marked asymmetric drift ($V_\theta = 133 \pm 19$ km s$^{-1}$, compared with a circular velocity of 231 km s$^{-1}$ (Feast & Whitelock 1997)). Whilst this group is small (18 stars) it shows rather clearly a mean outward motion, $V_R$, of $75 \pm 18$ km s$^{-1}$. In addition the individual space motions show that there is a rather good correlation between $V_\theta$ and $V_R$ in this group and all 11 stars which have an asymmetric drift greater than 65 km s$^{-1}$ having positive values of $V_R$ (see fig. 1 and Feast and Whitelock 2000a, Feast 2002).

Since many of these stars, all of which are within about 1 kpc of the Sun, are on highly eccentric orbits and will pass through, or close to, the Galactic Bulge, it seems likely that they are members of a bar-like distribution. It is known (Whitelock & Catchpole 1992) that the Miras in the Bulge itself belong to a central bar structure. A simple model would fit this suggestion for the local Miras although the possibility that they are part of a stream due to an infalling satellite galaxy, cannot be ruled out (see Feast and Whitelock 2000a and Feast 2002 for details). It is evident that a detailed study of this phenomenon requires space motions for short period Miras over a wide region of the Galaxy. This will be possible with GAIA parallaxes, proper motions, radial velocities and periods. It remains to be seen whether auxiliary data will be require to separate out the SP-red Miras which have different kinematics.

Related to this problem is that of the Galactic Bulge itself where, as just mentioned, Miras show a bar-like distribution. The Bulge contains Miras of a wide range of period and GAIA should allow the kinematics and structure of the Bulge to be explored in detail as a function of period using positions and space motions.

3. The C-Miras and S-type Miras

An extensive discussion of the carbon-rich Miras is beyond the scope of this talk. However the parallaxes, proper motions, radial velocities, periods and spectra which GAIA will provide should answer a number of outstanding problems connected with these objects. The space motions of C-Miras are of importance in their own right and will show how closely these stars are related to the O-Miras of the same (or a different) period. Whilst it seems likely that C-Mira evolve from O-Miras this is not yet certainly established. If indeed this is their evolutionary path, it is still uncertain whether they change period in the process.
Figure 1. The correlation between $V_\theta$ and $V_R$ for short period, blue-sequence, Miras. The solid line is from the simple model of Feast & Whitelock 2000a. The dotted oval shows the region occupied by the “Hercules” stream (see Fux 2001 and Feast 2002). The asterisk is for S Car which is on a highly eccentric retrograde orbit.
Space motions derived by GAIA will also be important for the understanding of the Miras with spectra of type S. These show strong zirconium oxide bands and lines of s-process elements are enhanced. These stars, which are oxygen-rich, are generally treated together with the O-Miras which have strong TiO bands. There is no clear dividing line between Miras with M type and those with S type spectra, the classes merging into one another (the MS stars). The extensive spectral and other data on O-Miras from GAIA may make it possible to divide them into groups which are more clearly defined and should lead to a much clearer understanding of this whole group of stars, their place in stellar evolution and their use in Galactic and extragalactic astronomy.

4. The Low Amplitude, Semiregular Variables

In this review a detailed discussion of the low-amplitude semiregular cool variables (the SR stars) has been omitted. However GAIA will almost certainly bring considerable order into this field which at present is in a rather unsatisfactory and confused state. In globular clusters, SR variables evolve with increasing period and luminosity (see e.g. Whitelock 1986, Feast 1989). They may change pulsation mode as they do so. In the LMC there are several sequences of semiregular, or low amplitude, variables in the period-luminosity plane, probably indicating several different pulsation modes (Wood 2000). The GAIA data will presumably reveal similar sequences in our own Galaxy (though infrared photometry of the relevant objects will probably be necessary to do this). With this done the kinematics, based on space motions, of the semiregulars divided according to particular period-luminosity sequence and to period, will help establish their evolutionary relationship. In view of the somewhat surprising results discussed above for the short period O-Miras, it seems very desirable that any kinematic analysis of these stars uses the full space and velocity co-ordinates. The spectra together with the photometry also opens up a largely unexplored area.

5. Deviations from the Mira Period-Luminosity Relation

If our ideas based on the Magellanic Clouds, globular clusters and the Hipparcos results on local Miras, are correct, it can be anticipated that in any volume of space in the Galaxy most of the regular, large amplitude, cool variables measured by GAIA will be Miras on the PL relation (either O- or C- Miras). Together with infrared photometry GAIA will establish the slope of this relation and its zero-point. The parallaxes will also enable one to find Mira or Mira-like stars that lie off the PL relation. Some stars of this kind are expected and their luminosities, space motions and spectra will be of great interest.

The SP-red Miras which seem to lie above the main PL relation were mentioned in section 2. But there are other types of Mira or Mira-like stars as well which are expected to lie off the PL relation. Towards the end of their AGB evolution, stars with initial masses in the range 4 to 6 solar masses can undergo Hot-Bottom-Burning (HBB). In this process the base of the H-rich convective envelope dips into the H-burning shell. The luminosity can then rise above that predicted by the classical relation between core-mass and luminosity. Carbon is burned to nitrogen and the beryllium transport mechanism results in an
overabundance of lithium at the surface. Whitelock (2002, see also Whitelock & Feast 2000b and references there) has pointed out that most of the AGB variables in the Magellanic Clouds in which Smith et al. (1995) found lithium to be strong lie above the Miras PL relation. The frequency of occurrence of these stars and their kinematics are obviously of great interest since they give clues to lifetimes and initial masses. Whitelock (2002) points out that the HBB phenomenon can explain a curious result found for LMC Miras. The evidence, which she summarizes, suggests that most LMC Miras with relatively thick dust shells and periods in the range 420 to 1300 days lie on an extension of the (bolometric) PL relation defined by shorter period Miras. These longer-period stars may be of sufficiently low mass that they never undergo HBB. However she points out that the few Miras with periods greater than 420 days and rather thin dust shells which seemed to indicate a break in the PL relation at that period in earlier work (Feast et al. 1989) may in fact be higher mass stars in a HBB phase. A full understanding of these phenomena is important not only for stellar evolution theory but also for the use of Miras as extragalactic distance indicators. For instance Whitelock (2002) suggests that the 641 day variable in IC1613 (Kurtev et al 2001) which lies well above the Mira PL may be in the HBB phase.

It has long been thought that the slow changes in period of some Miras (e.g. R Hya, see above) are due to the star undergoing helium shell flashing (thermal pulsing) (Wood & Zarro 1981). This is expected to be accompanied by changes in luminosity (e.g. Iben & Renzini 1983). Thus we may expect to find variables both above and below the PL relation due to this phenomenon. However the behaviour of R Hya is complex and the thermal pulse model has recently been challenged by Zijlstra et al. (2002) who suggest instead an envelope relaxation model.

Finally one should mention the possibility of finding dust-enshrouded OH/IR Miras below the PL relation. There is some evidence for such stars in the region of the Galactic Centre (e.g. Blommaert et al. 1998, Wood et al. 1998) but the bolometric luminosities of these stars are difficult to estimate accurately.

6. Red Supergiant Variables

Especially near the Galactic plane, GAIA will measure red supergiant variables. These objects show bolometric or infrared period-luminosity relations in, for instance, the Magellanic Clouds and M33 (Kinman, Mould & Wood 1987, Mould et al. 1990, Feast 1992). More recently, and of more direct relevance for GAIA, period- luminosity relations in the I-band have been established in Per OB1, LMC, M33 and M101 (Pierce, Jurcevic & Crabtree 2000, Jurcevic, Pierce & Jacoby 2000). In the I-band these red supergiant variables are about three magnitudes brighter than the classical Miras at a given period. The range in periods in Per OB1 suggests that the PL relation there is an evolutionary sequence in contrast to the Mira PL relation which is a mass/metallicity sequence, as discussed above. The PL relation established by Pierce et al. has a considerable RMS scatter (0.42 mag). This may be partly observational. It remains to see whether this PL relation is influenced by initial mass,age, or metallicity . These stars should be detected by GAIA to large distances even in the galactic plane.
and should be excellent tracers of the distribution and kinematics of young objects. The radial velocity component will be vital to study the kinematics properly.

### 7. Some Special Challenges

There will be a number of special challenges to be met in the interpretation of GAIA observations of Mira variables. One challenge is of course that we are moving into a little explored area. For instance, there are few, if any Miras that have been studied systematically round their light cycles for spectroscopic and radial velocity variations in the spectral region of interest to GAIA. The complex structure of Mira atmospheres and its variation with phase is not yet properly understood. References to high resolutions studies and their interpretation, from the early work of Merrill to the present are conveniently summarized by Alvarez et al. (2001); see also the summary of Lebzelter and Hinkle (2002). In the optical and infrared regions doubling of absorption lines is seen. Typically the lines are split by $\sim 20\,\text{km}\,\text{s}^{-1}$ in the optical region. At resolutions too low to show the splitting clearly, the variation in measured absorption line velocity round the cycle is probably $\sim 10\,\text{km}\,\text{s}^{-1}$ or less, though there have been no studies in the optical region as extensive those of Joy (1954) on Mira Ceti itself. There are variations of absorption line velocities with excitation potential, presumably due to the different depths of formation of the lines. The line doubling is thought to be due to shock waves in the atmosphere. These are also believed to excite the emission lines seen at some phases. In the past there has been some uncertainty about the definition of the actual radial velocity of a Mira in space. This is now generally taken to be the mean of the velocities of the two OH maser peaks which are found in some Miras. From a large body of data, generally involving only a few optical velocities for any given Mira, it is found that the mean absorption line velocity is too positive by $4\,\text{km}\,\text{s}^{-1}$ with some dependence on period (Feast and Whitelock 2000a). This offset may be due to most of the optical velocities having been obtained in the brighter half of the light cycle. Perhaps of more relevance, so far as GAIA spectroscopy is concerned, is the fact that some Miras, at least, show emission in the CaII infrared lines near maximum light. At least in some cases these lines have inverse P-Cygni profiles with velocity separations of $20-30\,\text{km}\,\text{s}^{-1}$ (Merrill 1934, 1960). Clearly, this must be taken into account in deriving mean velocities and space motions using these lines. The systematic study of the CaII lines round the light cycles of many Miras will be very revealing of the complex dynamics of Mira atmospheres.

A challenge, which affects particularly the astrometry, is the large angular size of the Miras. The diameters of Miras are a strong function of wavelength (e.g. Labeyrie et al. 1977). In a broad optical band, which is probably relevant to GAIA, the Mira R Leo and the Mira-like (SRa) star W Hya have mean angular diameters of 74 and 84 mas. These stars do not have circular symmetry and show evidence for asymmetric light distributions over the discs, possibly due to large star-spots (Lattanzi et al. 1997 and references there). The diameters of these stars are greater than the expected point spread function of GAIA. They are also nearly a factor of ten greater than their Hipparcos parallaxes (or the parallaxes derived from the PL(K) relation of Feast et al. (2002)). Thus the
8. Conclusions

The combination of GAIA astrometry, radial velocities, spectra, photometry and periods will have a profound and unique effect on our understanding of the nature and evolution of cool variable stars, particularly those on the AGB. Also the kinematics of these objects will allow us to study the structure and evolution of Our Galaxy in a way previously impossible. Hipparcos already led to surprises in this area and gave some foretaste of what GAIA will accomplish.

It would be rather valuable if ground-based observers gave some thought now to parallel programmes which would be completed by the time the results from GAIA become available. In the optical/infrared field some obvious programmes in this category are; interferometry, intensive infrared photometry and high resolution optical spectroscopy.

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