Red Giant Variables

Ian Glass (isg@alum.mit.edu)

Red giant variables, bright in the infrared and important contributors to the interstellar medium, were one of the main themes of my research and what follows is a summary of my contributions (of course, with collaborators), not a general review. As will be noticed, my approach has been fairly strictly empirical.

The Mira Period-Luminosity Relation

The search for a period-luminosity relation for Miras had a long history, with attempts having been made by *inter alia* Gerasamovič (Proc Natl Acad Sci USA **14**, 963, 1928) and Clayton and Feast (MNRAS **146** 411 1969), using galactic Miras whose distances were only roughly modelled through "statistical parallaxes" and photographic magnitudes.

The blue/visible regions in which these attempts were made are however in retrospect fundamentally inappropriate because the spectral energy distributions of Miras are heavily affected by deep and broad absorption bands in visible light, making it impossible to define continuum levels. In addition, most of their energy emerges at near-infrared wavelengths. The early attempts were consequently not very conclusive.

I believe the idea of looking at Large Magellanic Cloud (LMC) Miras in the infrared arose in casual conversations with Louise Webster and Tom Lloyd Evans during my visits to Radcliffe Observatory in the early 1970s. Lloyd Evans had discovered a number of Miras in a dense field of the LMC using the traditional very laborious method of blinking plates. He had determined periods and could tell which were C stars from their relative faintness in the B band. He had however never published their positions (see *The Magellanic Clouds* ed Muller AB, p74, 1971 and *MNRAS* **183**, 305, 1978) but when he joined the SAAO he was amenable to letting me have access to his finding charts and I began to observe them from about October 1976 onwards until August 1980, more frequently towards the latter date.

They were difficult to observe because their coordinates had not been determined very accurately and they were faint and even effectively invisible when at minima. They sometimes had to be searched for at infrared wavelengths using area scanning. The advent of integrating television helped considerably to find them, in part because the camera was most sensitive at the red end of the spectrum. The fields were very crowded, sometimes leading to contamination of the reference beam fields of the star-sky choppers and necessitating non-standard chopping distances.

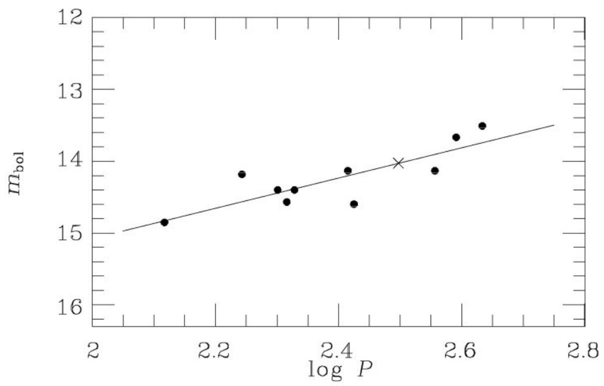


Fig 1: The first K, log P diagram for Miras. The X denotes a carbon Mira.

K. log P and m_{BOL}, log P relations were derived for the sample. The dispersion about the relation was promisingly small, less than that for classical Cepheids (if no Cepheid colour term was included). Interestingly the one carbon Mira lay along the same relation. Their periods ranged from 131 to 430d. There was obvious potential for the use of Miras as distance indicators.

This result was published (*Nature* **291**, 303, 1981) by Glass and Lloyd Evans.

Not very long afterwards a more detailed paper giving the individual observations was written (Glass & Feast, *MNRAS* **199**, 245, 1982) comparing the properties of LMC Miras to galactic ones.

Lloyd Evans had also examined a field in the Small Magellanic Cloud for large amplitude long-period variables. These were examined by infrared photometry and found to be similar in general character to those of the LMC. The proportion of C-stars was higher in the SMC than the LMC (See Lloyd Evans, Glass and Catchpole, *MNRAS* **231**, 773, 1988).

Refining the P-L Relation

This result deserved to be refined by increasing the sample size in the LMC and making further infrared measurements. The UK Schmidt telescope was used by Wood, Bessell and Paltoglou (WBP, *ApJ* **290**, 477, 1985) to produce further discoveries. Glass & Reid (*MNRAS* **214**, 405, 1985) used 3 V- and 5 I-band plates, scanned with the COSMOS machine in Edinburgh, to find around 40 variables with periods for 24 of them. Eventually, a total of 23 I plates were obtained and used to determine periods. Each star was observed at JHK (and L if possible). This programme was extended to another 70 variables by Reid, Glass & Catchpole (*MNRAS* **232**, 53, 1988). Somewhat over 1/3 of the sample were carbon stars and about 10% were more luminous M-type variables likely to be younger and more massive. The latter groups of stars differed obviously from the more typical M-type Miras in the (J-K), K colour-magnitude diagram. The (J-H), (H-K) two-colour diagram showed reasonable agreement between LMC M-type Miras and galactic ones.

In general, the proportion of C and to some extent S stars increases in the sequence Galaxy, LMC, SMC. This is a reflection of decreasing metal content. Another consequence is that the visual amplitudes of the M stars tends to be lower in the Magellanic Clouds because of the lesser effect of TiO absorption.

The MIras then known (which included the WBP Miras) were plotted on the K, log P diagram. Again, the carbon Miras fell on the same line as the M-types. The group of more luminous variables fell above the relation and did not include C-types. The C-types tended to be more luminous than the M-type Miras but to have an upper limit at $M_{BOL} \sim -10$.

The K, log P relations for LMC Miras were found to be similar to those for Miras from other environments, such as the SMC, galactic globular clusters and the Galactic Centre.

The P-L relation at the Calgary Conference, 1987

Reid had continuously expanded the number of known LMC Miras. As it was obvious that many more infrared observations had to be made, Catchpole, Feast and Whitelock also took part in the observational programme. For a conference at Calgary in 1987 I prepared a paper that showed how tight the K, log P and the M_{BOL}, log P for Miras and the total sample actually are (See Figs 2 & 3 from Glass, Catchpole, Feast, Whitelock and Reid, in Kwok & Pottasch (eds), *Late Stages of Stellar Evolution*, Reidel, 1987, GCFWR).

The plotted magnitudes were the average of the maximum and minimum observed amplitudes.

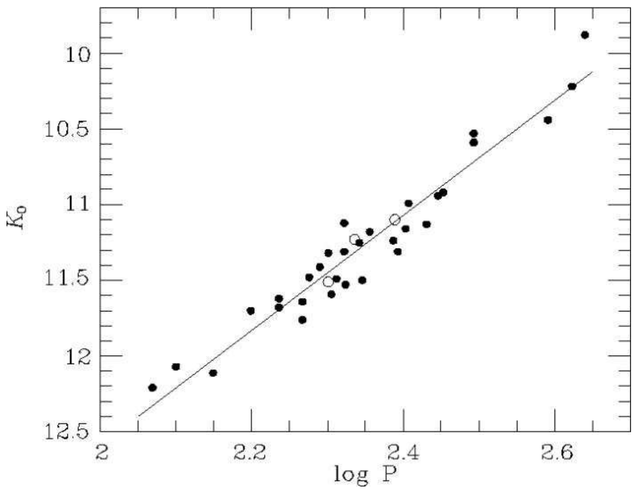


Fig 2: K, log P diagram for M stars from GCFWR, 1987, Fig 3). The open circles are S stars. For the whole group of 75 stars, the dispersion about the K, logP fit was 0.17 and for the M and S stars only it was 0.13.

The m_{BOL}, log P diagram shows greater scatter. For the M and S stars alone, it is 0.16. However, the C stars usually fall considerably below the M & S fit , probably due to greater molecular absorption in the other bands.
The M, S fit was

$$K_0 = (-3.79 \pm 0.18) \log P \text{ (days)} + (20.17 \pm 0.42) \quad \sigma = 0.13$$

In 1989 I drafted a final paper in this series which was re-written by Feast, elaborating on previous results with the addition of rather marginal colour terms in the relations (Feast, Glass, Whitelock and Catchpole *MNRAS* **241,** 375, 1989). The fit to M-type Miras was slightly different:

$$K_0 = (-3.47 \pm 0.19) \log P \text{ (days)} + (19.48 \pm 0.45) \quad \sigma = 0.13$$

In 1995 a final paper of the Reid LMC discovery series (Reid, Hughes & Glass *MNRAS* **275**, 331, 1995) presented data for 302 periodic variables, with JHK infrared data for 276 of which 190 are Miras. Most of the previously noted trends were confirmed with the better samples. There was no definite trend in I mag vs period, in effect implying that the (I-K) colour becomes redder at longer periods.

The Mira P-L relation after including the MACHO data

With the publication on-line of data from the MACHO experiment (Alcock et al, *AJ,* **119**, 2194, 2000), visible-region photometry in b and r became available for millions of stars in the LMC. Each one had up to 1000 observations. I searched for the defining stars of the P-L relation among these to find their light curves and was able to derive improved periods for almost all of them as well as to eliminate three stars that were SR variables rather than Miras. (*MN* **343**, 67, 2003) Positions, spectral types, amplitudes, and variations in amplitudes were determined

The resultant P-L relations were not significantly different from the earlier ones: for example, for the 26 M-type Miras in the sample we have:

$K = (-3.52 \pm 0.21) \log P + (19.64 \pm 0.46), \sigma = 0.13$

The periods evidently remained substantially constant over the intervening 3 decades.

In addition, it was noted that the Carbon stars in general had smaller amplitudes than the M-types. The group of variables more luminous than the Miras (suggested by Whitelock and Feast *Mem Soc Astr Ital* **701**, 601, 2000) as being 'Hot-Bottom Burners') often show a minor bump or peak on their rising branches. Their r amplitudes ranged up to nearly 5 mag whereas the K amplitudes were usually less than 1 mag. Two of the latter stars showed enhanced Li in their spectrum, tending to confirm the HBB hypothesis.

The K amplitudes were found to vary to some extent over several cycles and could account for a lot of the scatter in the K, log P relation.

Miras in the Baade's Window fields near the Galactic Centre

When the IRAS Catalogue appeared, Feast (1985) showed that about half of the IRAS sources in the Baade's Window fields could be immediately be associated with Miras that had been found in the visible and photographic infrared by Lloyd Evans (*MN* **174**, 169, 1976: TLE). I manually scanned the remaining IRAS error boxes and found that they are also likely to be Mira variables that were visually faint due to being of very long period or obscuration by thick dust shells (*MNRAS* **221**, 879, 1986).

It was obvious that to get a full picture of the Mira content of the field observations at visible and infrared wavelengths have to be combined (see Fig 3).

The Sgr I MIras had to be investigated further because the Baade's Window Sgr I field is the closest to the Galactic Centre where stars can be examined at visible wavelengths and therefore a lot is known about them. Further, determination of the K-band magnitude of the Miras in conjunction with the Period-luminosity relation offered a new way of obtaining the distance to the Galactic Centre. This project required a great many observations and was joined by Whitelock, Catchpole and Feast.

The results (Glass, Whitelock, Catchpole, Feast *MNRAS* **273**, 383, 1995) were of great interest. Some 63 Mira-type variables were observed around 10 times each at JHKL.

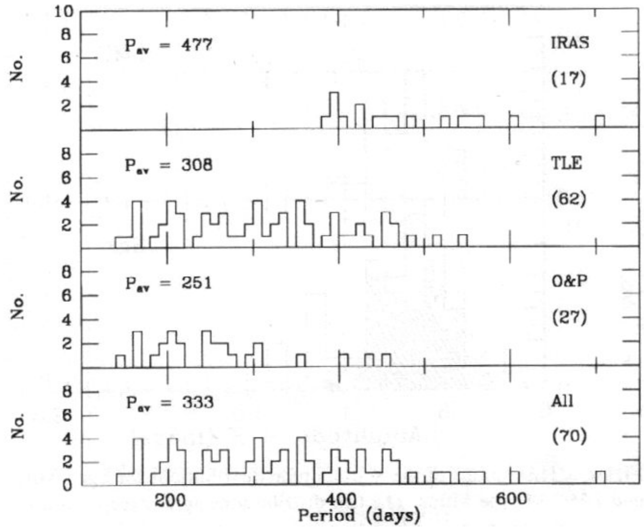


Fig 3: No of Miras found in the Sgr I field by various methods. IRAS (top) found mainly long-period stars. TLE using V, I photographic plates found all but the longest periods. Osterhof & Ponsen (bull Astr Insts Netherlands Suppl Ser, 3, 79, 1968) had found only the shorter periods using B plates.

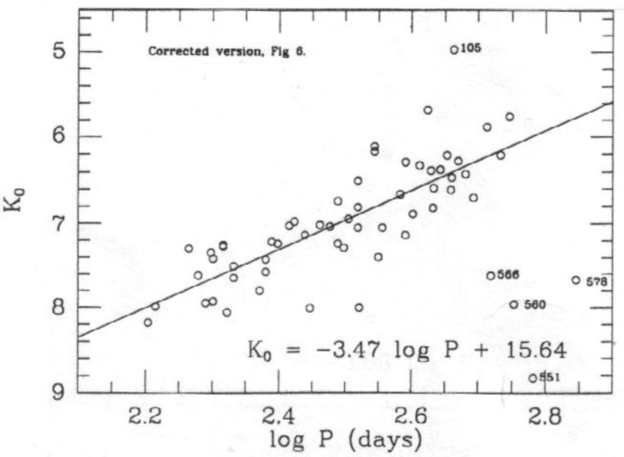


Fig 4: K, logP diagram for the Sgr I field with relation found. The scatter was σ = 0.35, probably due for the most part to the finite depth of the field.

The slopes of the relations are consistent with those of the LMC. If the distance modulus of the LMC is taken to be 18.55, the distance to the Galactic Centre from Miras is 8.7 ± 0.7 kpc.

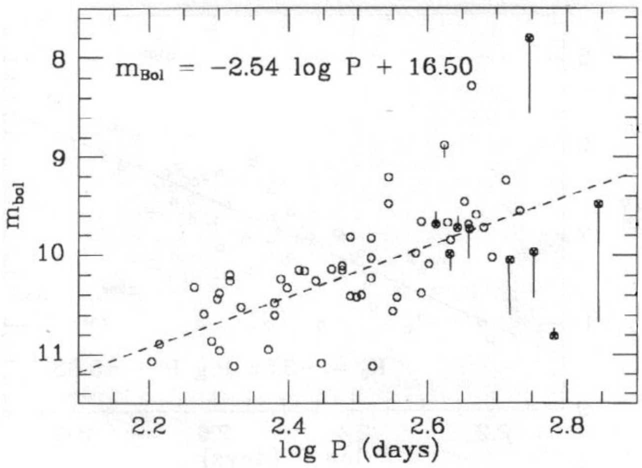


Fig 5: The m_{bol}, logP relation for Sgr I Miras. The fit is for the TLE Miras, excluding IRAS data; σ = 0.36. *The points with lines attached include IRAS long-wavelength data in the calculation of the magnitudes. The other ends of the lines show the effect of omitting the long-period data, showing that a significant fraction of the radiation is emitted by dust shells.*

Mid-infrared (ISOGAL) Survey of Baade's Windows

ISOGAL (PI Alain Omont) was an observational programme that surveyed low galactic latitude fields at ~7 µm and ~15 µm using the ISO infrared satellite. These were obviously going to be regions of high extinction and little was known as to their likely stellar contents. I therefore suggested to the ISOGAL consortium that they should include the Baade's Windows NGC6522 and SgrI as these areas had been well-surveyed and could provide a basis against which obscured areas could be compared. In addition to the long-period variable work of Lloyd Evans already described, Blanco, McCarthy and Blanco (*AJ* **89,** 636, 1984, BMB) and Blanco (*AJ* **91**, 290, 1986) had made spectroscopic surveys of late type stars in NGC6522.

I was able to join the ISOGAL group as an associate member and made a number of fruitful visits to the Institute of Astrophysics in Paris to collaborate with Omont, Mathias Schultheis, Shashikiran Ganesh and others. I here express my gratitude to Prof Omont for his support of this work and my visits.

The results from ISOGAL were every bit as interesting as we had hoped. They showed that most of the objects detected were late-type giants on the AGB, with a cut-off for those earlier than M3-M4. The most luminous objects at longer wavelengths were the Mira variables.

Dust emission from Semiregular variables - 1

A group of late M stars (see Fig 6) was found that were not known to vary but had infrared colours typical of well developed dust shells. Their luminosities were similar to those of the 200-300 day Miras. A number of these were selected for further study. They appear on Lloyd Evans's I plates, and were re-checked by him but they did not obviously seem to vary, though there were some suggestions that they might be semiregular variables with much lower amplitudes than the Miras (see Glass, Ganesh, Alard, Blommaert, Gilmore, Lloyd Evans, Schultheis and Simon *MNRAS* **308,** 127, 1999).

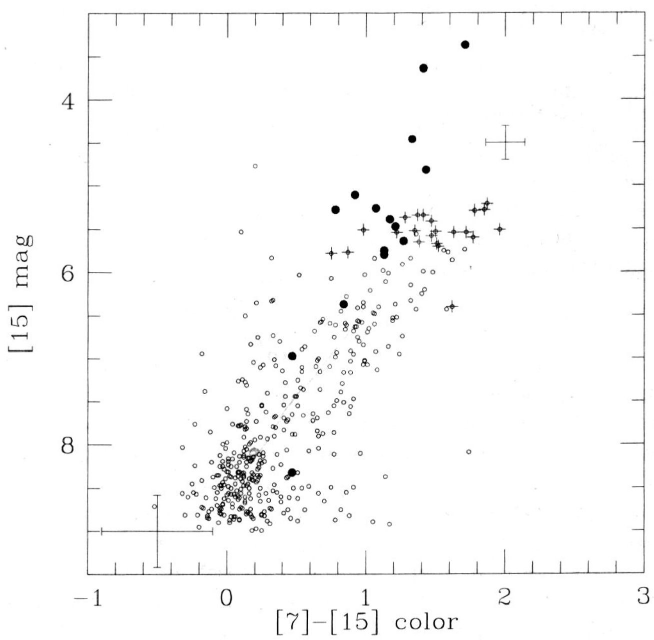


Fig 6: Combined ISOGAL data from the fields in the NGC6522 and SgrI windows. The 15μm flux increases with [7] – [15] colour. The filled circles are Mira variables and the crosses are bright stars that were examined unsuccessfully for variability in the pre-MACHO data. Representative error bars for faint and bright stars are given. Note that the colours of the Mira variables seem to be less red than for the other stars of similar [15] mag.

A similar analysis, extended to include matching of ~90% of the ISOGAL sources with near-IR photometry from the near-infrared DENIS IJK survey showed that the [15] vs K - [15] points were fairly closely correlated. The long-wavelength data clearly revealed the existence of dust shells that were not obvious from the near-infrared data (see Omont, Ganesh and 22 others including Glass, *A & Ap*, **348**, 755, 1999).

DENIS and ISOGAL Variable Star Candidates in the Bulge

DENIS was an IJK survey of the southern hemisphere. Certain fields of the Bulge amounting to ~4 degree^2 were observed twice, about two yrs apart, and ~1000 stars were identified as having varied (Schultheis et al *A&A* **362**, 215, 2000). The detection rates for variables were estimated by comparison with the results of the Glass et al variable star survey published in 2002, for the region of overlap. It was concluded that some ~40% of large amplitude variables would have been detected and that about 20% of the candidates were spurious.

Using the extinction map of Schultheis et al (*A&A* **349**, L69, 1999) based on isochrones fitted to the DENIS J and K data, it was possible to de-redden the variable star photometry, for A_V not exceeding 25 mag, and to construct colour-magnitude and colour-colour diagrams. Most of the variables were above the RGB tip and therefore on the AGB.

One of the ISOGAL fields was observed more than once in both surveys and 7 out of 11 DENIS variables were also seen to vary in ISOGAL LPVs are easily distinguished as bright and red in the K-[7]/[7] colour-magnitude diagram.

Dust emission from Semi-regular Variables - 2

It was desirable to investigate the non-Mira sources in more detail with more accurate photometry than Lloyd Evans's photographic method had provided.

At around this time, results were beginning to become available from the MACHO consortium concerning variables in the Baade's Windows and the Magellanic Clouds. Wood et al (MACHO collaboration, IAU Symp 121, ASP, p169, 1999) had made an analysis of LMC stars showing the existence of a number of sequences among SR variables in the LMC magnitude, log P diagram. However, only members of the consortium had rights to the data at the time. Consequently, I made an application for access that was circulated to the members of the consortium and David Alves of STScI offered to collaborate.

Matches were made between the ISOGAL and the MACHO positions for the NGC6522 and SgrI Baade's Window fields, producing 332 stars with detailed photometry at v,r, [7] and [15]. Almost all of the 332 show variability at some level and all but the few Miras present can be classified as Semi-regulars.

It is evident that the numbers of SR variables in the Bulge population greatly exceeds the number of Miras.

Fourier analyses of the MACHO photometry were made to obtain the predominant periods present in each star (for the initial results, see Glass, Alves and the ISOGAL and MACHO teams, *ISO Surveys of a Dusty Universe*, *Springer Lect Notes in Phys*, 548, p. 363, 1989).

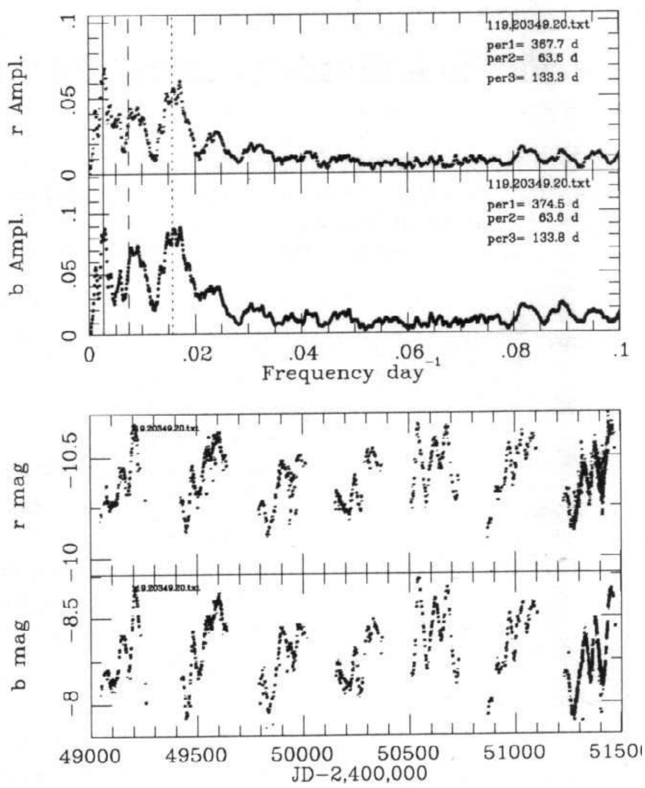
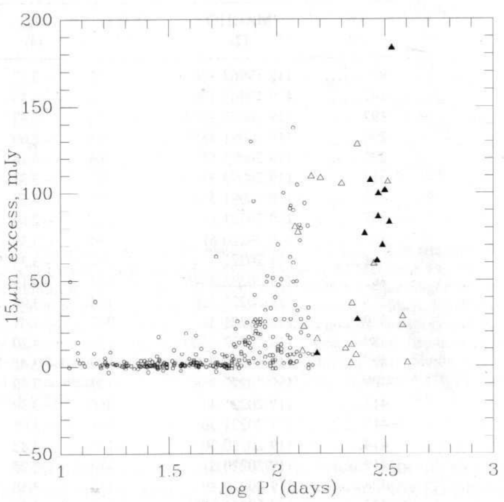


Fig 7: The lower panels show typical b,r data from MACHO for a SRV in the NGC6522 field. The upper panels show Fourier amplitude spectra of these data with the three most significant periods picked out. Though this particular star shows typical primary and secondary periods of 64 and 133d it also has a long secondary period of 370d.



The final result of this study was written by Alves and me, and the entire ISOGAL and MACHO teams were given as co-authors (Alard et al, *ApJ,* **552**, 289, 2001).

Fig 8: Excess 15µm fluxes in MJy, beyond what is expected by assuming a Rayleigh-Jeans photospheric energy distribution *fitted to the 7μm fluxes, shown plotted against log Period.* ***Having a period P > 60 days seems to be a necessary but not a sufficient condition for significant mass-loss*** *(Alard et al, 2001).*

An important result is that mass loss is detected in many SRVs with periods in excess of 60d. Another result of the study with Alves of the SR variables in NGC6522 was the attached diagram showing how the amplitude increases with log P.

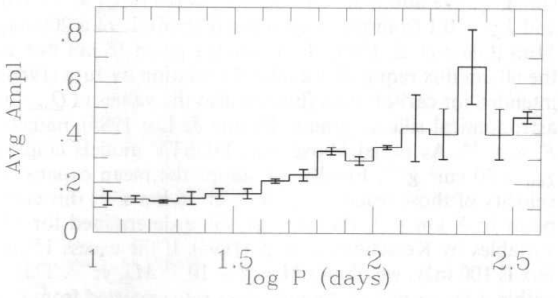


Fig 9: Amplitude of SR variables in NGC6522 plotted against log P, showing that the amplitude increases with period.

Ubiquity of mass-loss in late M giant stars

Many of the SR variables in the study above with Alves had spectra by Blanco et al (*AJ* **89**, 636, 1984) and Blanco (*AJ* **91**, 290, 1986). The question could then be addressed as to what extent M giants in general show variability and mass-loss.

The sample of 174 M stars in NGC6522 with spectroscopy by Blanco (1986) was consequently examined for variability from MACHO, for mid-infrared photometry from ISOGAL and for IJK from the DENIS near-IR survey (Glass and Schultheis *MN* **337**, 519, 2002).

We found that stars of classes M1-M4 do not show variability but many of those of M5 and later do so.

K brightens with later spectral subclass, I-J becomes redder as does J-K.

Almost all the variables were detected at 7 microns by ISO but detectable excess radiation at 15 microns was associated with high luminosity and later spectral type. The non-variables were not detected.

There was some evidence that in the K, log P diagram the relations discovered by Wood for SR variables in the LMC were followed but the numbers were too sparse for certainty.

The K, log P sequences in the NGC6522 Baade's Window

The hints of the Wood relations described above led us to investigate the issue of period-magnitude relations for M giants in Baade's Window NGC6522 more generally (Glass & Schultheis *MN* **345**, 39, 2003).

For this study we looked at all stars with K (Denis) < 9.5 in the NGC6522 window, extracting their light curves from MACHO.

Over 1000 variables were examined and it is clear that the main sequences identified by Wood in the LMC can also be seen in the NGC6522 field, albeit spread out by the finite thickness of the Bulge. There are some subtle differences, however, perhaps due to metallicity.

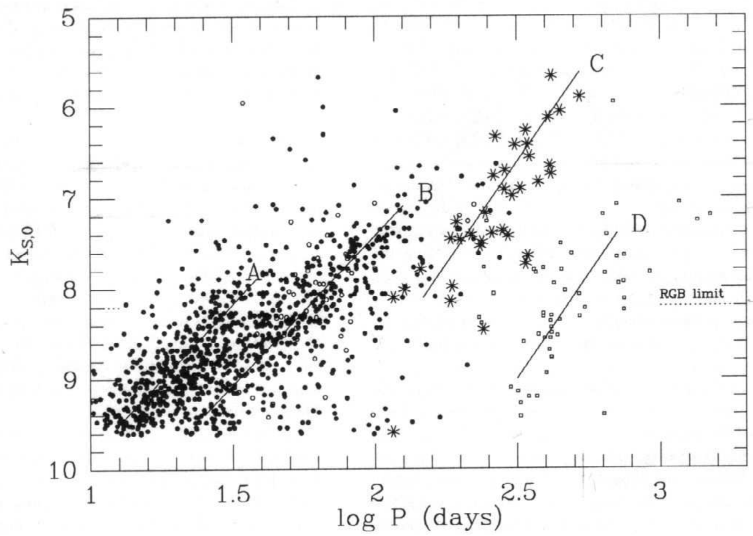


Fig 10: K, log P diagram for the NGC6522 field. The general distribution of stars in this diagram resembles those in the LMC and the SMC. Mst variables are shown as solid dots. Doubly periodic (ie short and long-period) variables are shown as open symbols. Large-amplitude stars are asterisks. The lines were fitted by eye. Four distinct sequences have been noted. The scatter is higher than in the LMC because of the finite depth in the field of view.

As noted by Wood et al 1999, the SRVs often show two short periods differing by factors of about 1.25 to 1.5 for periods up to about 50d.

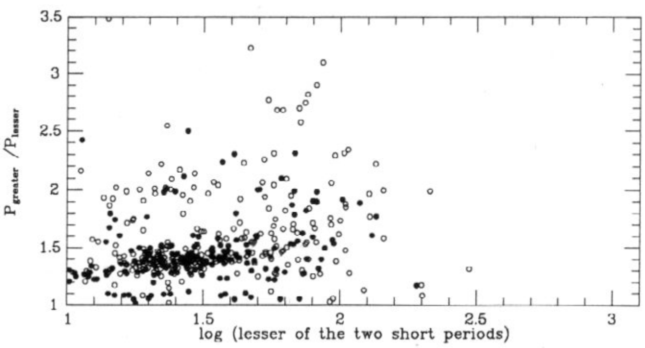
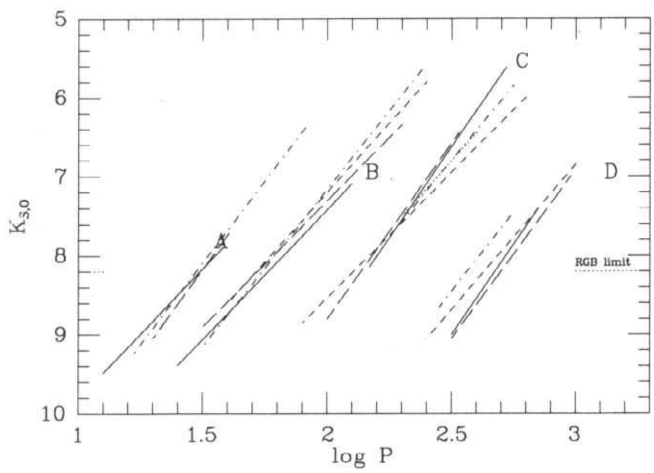


Fig 11: The ratio of the longest short period divided by the shortest short period plotted against the log of the lesser of the two short periods, as done by Wood et al (1999) for the LMC, showing similar results.

*Fig 12: The positions of the SRV sequences in the K, log P diagram as determined for the LMC (short dashes), Wood (Pub Astr Soc Aust, **18**, 18, 2000 long dashes) the SMC (dot-dashes Ita et al MN **347**, 720, 2004) and this work on the NGC6522 field (solid lines).*



The numbers of long-period variables – a general remark

It was interesting to make a comparison with the traditional view of the numbers of red variables of given amplitude as presented by Payne-Gaposchkin in 1951.

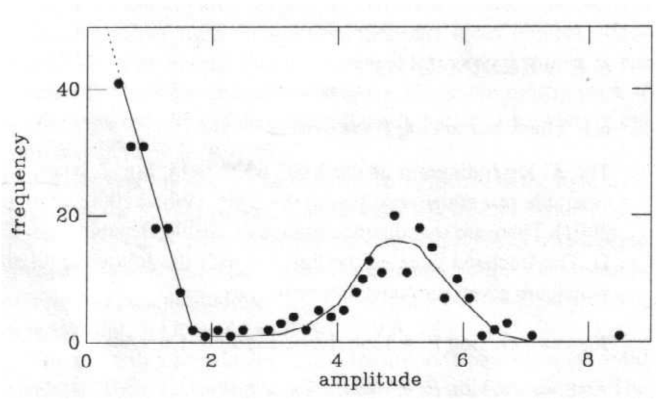


Fig 13: The frequency distribution of red variables of a given amplitude from Payne-Gaposchkin (in Hynek, Astrophysics, McGraw-Hill, 1951). Probably based on blue-region magnitudes.

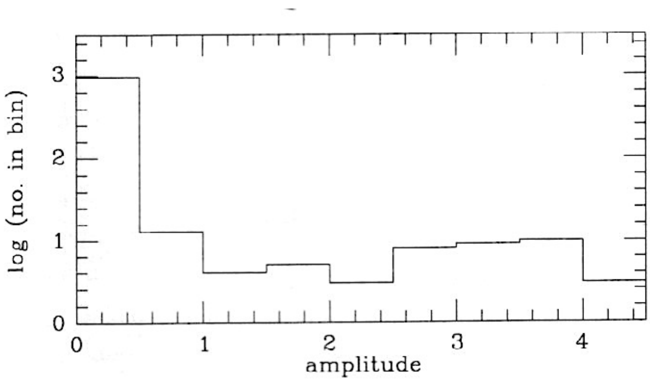


Fig 14: This diagram gives the r amplitudes of red variables in NGC6522 showing that there is a much more continuous distribution than was previously believed.

Implications for the SR Variables in the solar neighbourhood

Bedding and Zijlstra (*ApJ,* **506**, L47, 1998) used Hipparcos data to derive a M_K, logP diagram for nearby stars, of Mira and semi-regular variables.
Since the LMC and NGC6522 fields show similar sequences, we would expect their solar neighbourhood counterparts to show them also. Their SR sample was restricted to stars having relatively large amplitudes and so only the bright end of the sample is included. Their result can be simulated by artificially restricting the K log P diagram for NGC6522 to those with r amplitudes between 0.3 and 1.6 mag. The similarity is shown up.

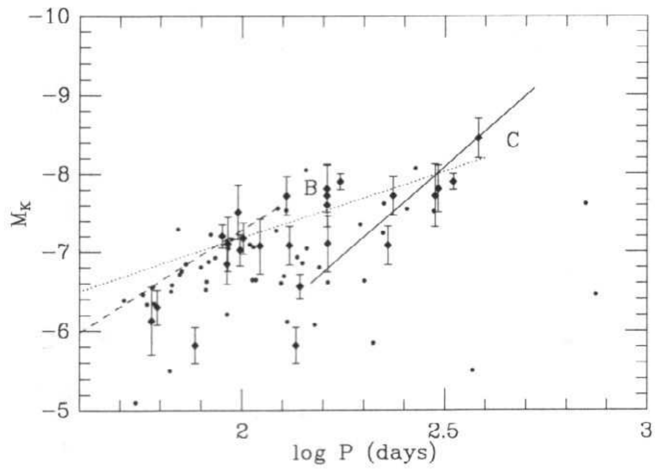


Fig 15: M_K, log P diagram of local Miras and SRVs from Bedding and Zijlstra (BZ, 1998) [the points with error bars] and stars chosen by amplitude from our NGC6522 sample. The dotted line is a suggested evolutionary track from a globular cluster

*(Whitelock, MN **219**, 525, 1986) adapted by BZ (1998)*

Population Differences among the late-type variables

Schultheis, Glass and Cioni (*A&A*, **427**, 945, 2004) extracted complete samples of 2MASS stars in three fields from NGC6522, the LMC and the SMC and cross-correlated them with MACHO and ISO data to examine this question. These fields have different metallicities and possibly age distributions.

A number of effects were noted with decreasing metallicity:

The luminosity of the red giant tip and the J-K colour for a given M_K decrease.

The colour indicies show that the proportion of carbon stars decreases.

The proportion of stars that vary decreases and the minimum period associated with a given amplitude gets longer.

In the M_K, log P diagrams (see Fig 16 below), the galactic sequences appear truncated relative to those in the Magellanic Clouds.

The differences in the ISO colour distributions at are dominated by the carbon star content.

Mira magnitude vs log P relations exist at least up to 7μm.

Mass-loss from longer-period and double-period SRVs occur at similar rates in each field in spite of the metallicity differences.

More on semiregular variables in the solar neighbourhood

In comparing the populations of the solar neighbourhood with those of the Bulge windows and the Magellanic Clouds there are several difficulties, the principal of which are the lack of precisely known distances and periods.

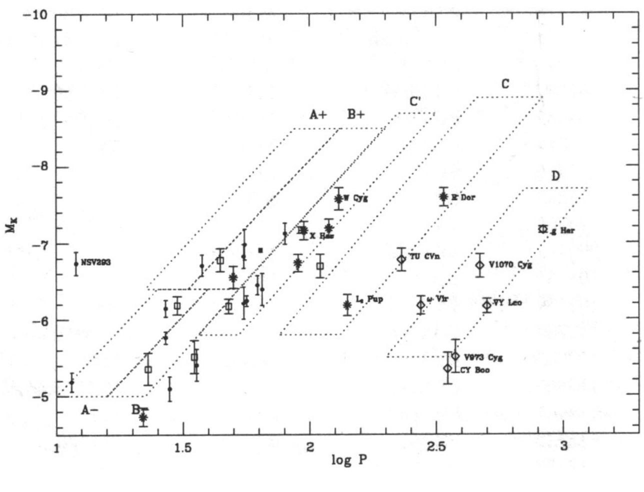


Fig 16: K, log P for local M giants with parallaxes greater than 10 times the probable error. The Ita (2004) categorisations are shown as dotted lines. Stars with V amplitude > 1 are shown as asterisks and double-period stars are boxes (short periods) and diamonds (long periods).

Glass & van Leeuwen *(MN* **378**, 1543, 2007) compiled a list of SRVs with revised Hipparcos parallaxes and known periods (many of the latter ambiguous or of poor quality).

By this time, more precise information on the loci of the LMC SRVs had been published by Ita et al (*MN* **2004**, 353, 705). It had become evident that the A, B, C and D sequences of Wood (*Pub Astr Soc Aust*, **17**, 18, 2000) have to be subdivided (as seen in the above figure).

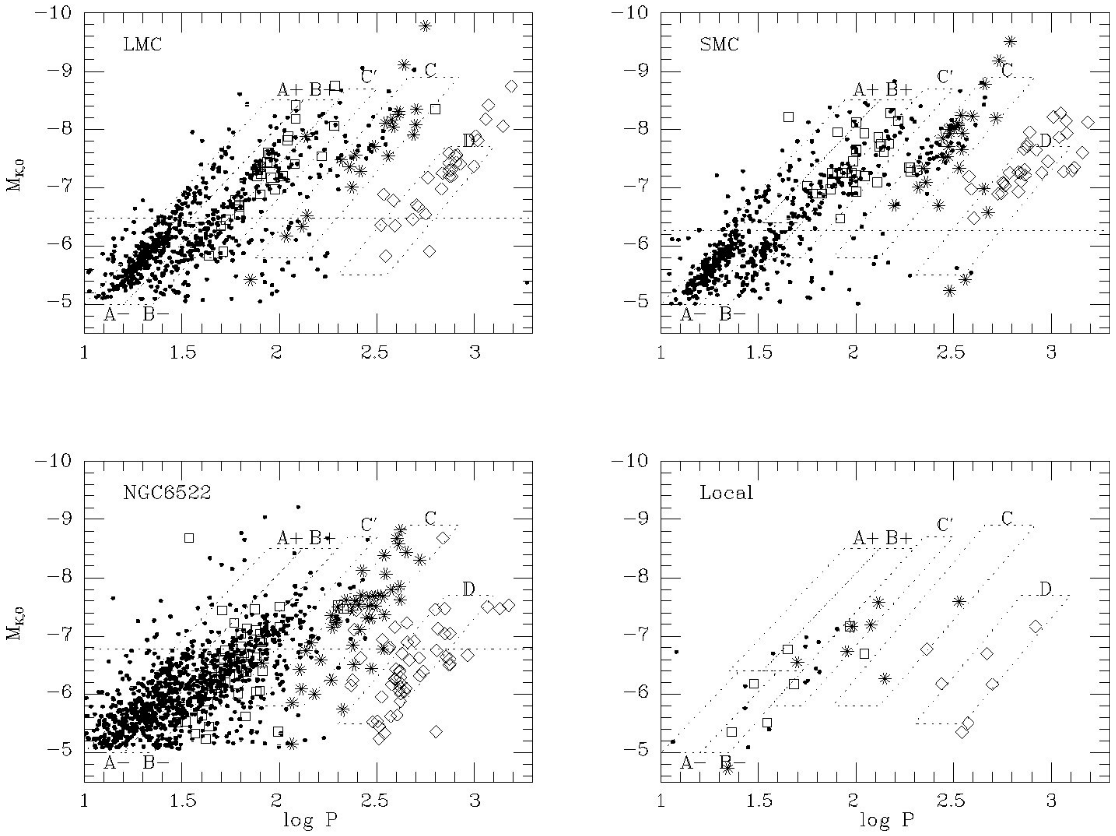


Fig 17: Comparisons of the M_K, log P diagrams from the two Magellanic Clouds with the NGC6522 field in the Galactic Bulge (from Schultheis et al op cit 2004).
To these have been added the local SRVs (from above). The distance moduli of the first three fields are taken to be 18.5, 18.94 and 14.7 respectively and the tops of their giant branches are shown as dotted lines. Note particularly that the A,B,C sequences of the Galactic SRVs do not reach such high K luminosities as the Magellanic Cloud ones.

Note: some of these issues (local SRVs and population comparisons) have since been discussed with different and/or better data by Tabur et al (see, for example *MN* **409**, 777 2010).

Prevalance of Mass-loss at long periods and late spectral types

12 µm mags for most of the local sample could be obtained from the IRAS Catalog. The K luminosities are mostly photospheric but the [12] mag is affected

by dust emission, like the [15] mags observed with ISO. Thus K – [12] colour is an indication of mass-loss. It is associated with large amplitudes of variation.

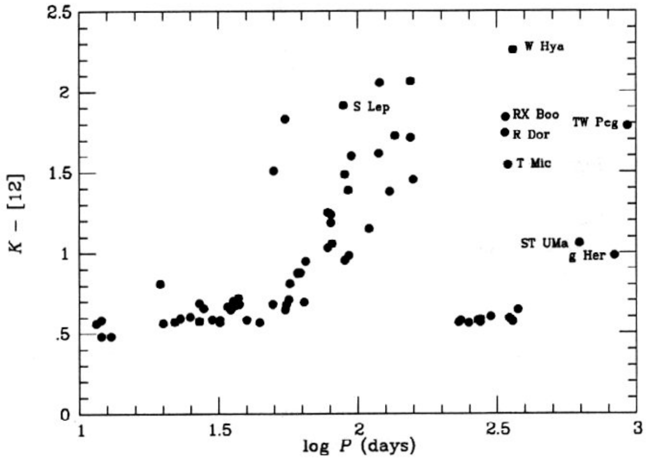
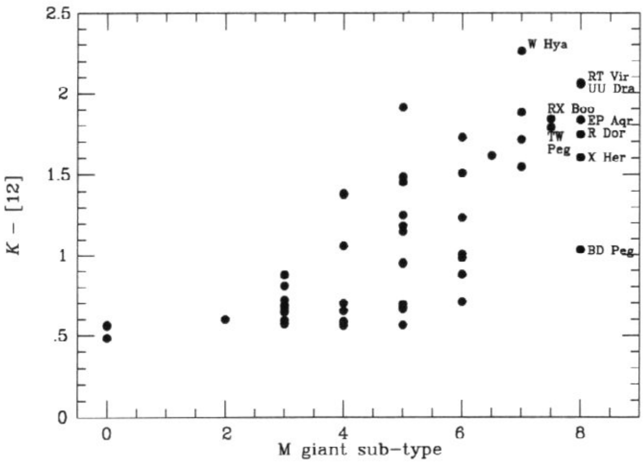


Fig 18: This diagram shows that noticeable mass loss starts at log P ~ 1.75, similarly to stars in the NGC6522 and Magellanic Cloud fields (Alard et al, (2001) op cit; Schultheis et al (2004), op cit)

Fig 19: A similar diagram for mass-loss against spectral type, showing that mass-loss sets in for later spectral types (see also Alard et al (2001), op cit, for NGC6522).



Mid-infrared period-luminosity relations

The Spitzer infrared satellite has surveyed fields in NGC6522 and the LMC at 3.6, 4.5, 5.8, 8 and 24μm. These data were used by Glass, Schultheis, Blommaert, Saha, Stute and Uttenthaler (*MN 395*, L11, 2009) to look for period-magnitude relations in the mid-IR. The LMC data form part of the SAGE programme (Meixner et al AJ 132 2268, 2006) and the NGC6522 were from the Galactic Bulge Giant Survey described by Uttenthaler et al *A & Ap* **517**, A44, 2010.

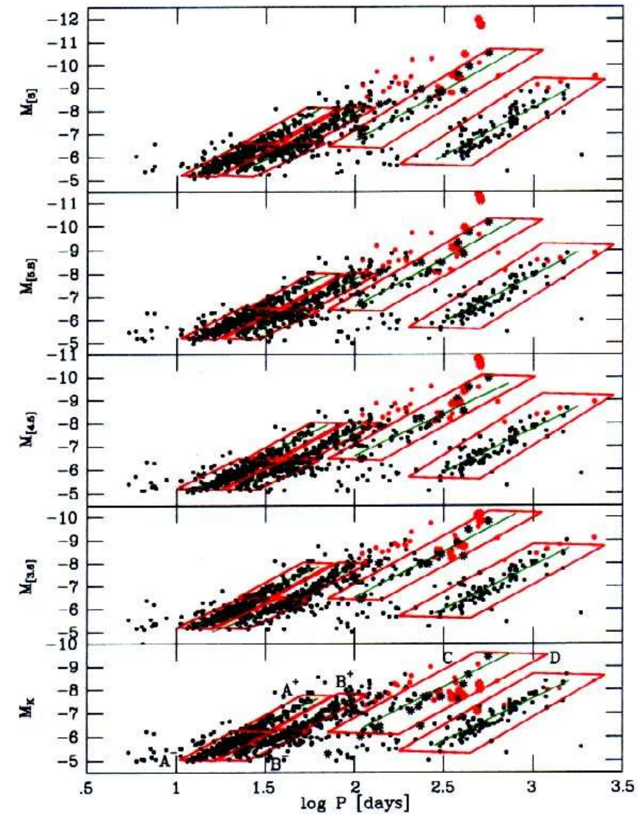


Fig 20: Log P vs Spitzer magnitudes. Red dots are the LMC SRVs, red crosses the LMC Miras, Magenta dots the LMC subsidiary long periods; black and green are the same respectively for NGC6522. Local AGB stars with synthetic photometry by Marengo et al (AIP Conf Proc 1001, 331, 2008) are shown in blue with X for M-types and + for C types. Note: the original published diagrams should be clearer and the Glass et al (2009) paper should be consulted for various caveats.

The principal M, log P sequences are again visible. Linear fits were made to the sequences (with some arbitrariness in their definitions) and the slopes were essentially similar, independent of waveband,

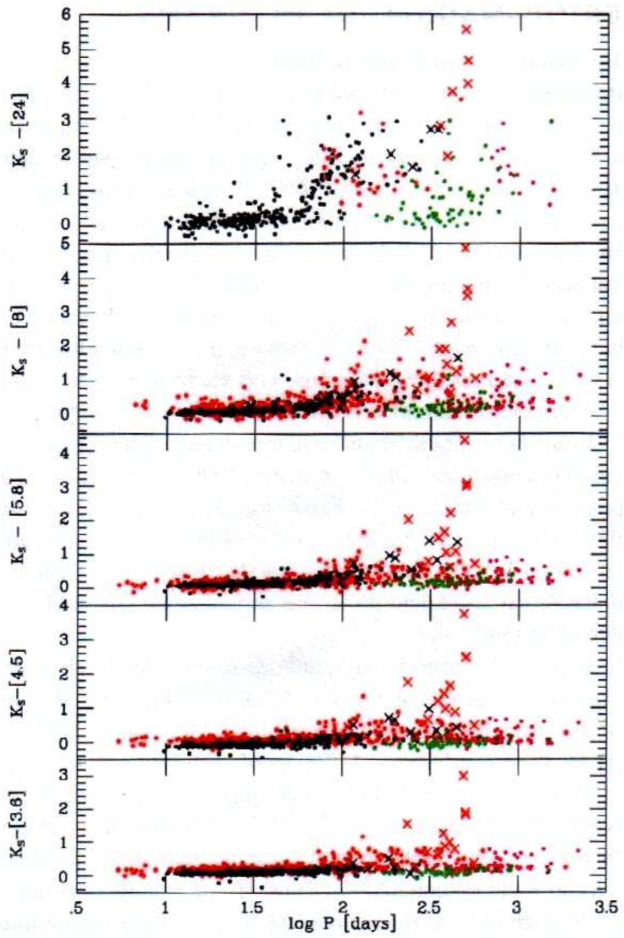


Fig 21: (K – Spitzer) colours vs log P, showing how the infrared excess due to dust emission become much more pronounced at longer wavelengths. Again, mass loss is seen to commence for log P > 1.75.

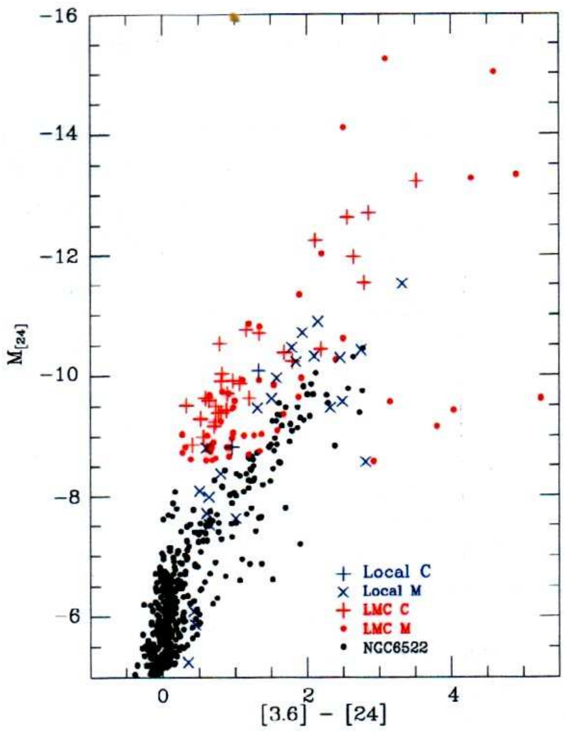


Fig 22: [24] mag vs [3.6] – [24] colours for the LMC and the NGC6522 field, including non-variables. Also local Miras from Marengo et al (2008, op cit). There is a bifurcation between the C and M stars in this diagram.

See Riebel et al (*ApJ*, **723**, 1195, 2010) for discussion of a much larger sample.

Mid-IR spectra of Galactic Bulge AGB stars

(Blommaert et al *A&A* **460**, 555, 2006)

These observations from the ISO satellite were made using a Circular Variable Filter and covered 5 to 16.5 µm. Likely AGB variables were examined from 3 fields, with DENIS IJK , 2MASS JHK and ISOGAL [7] and [15} mags also available.

The luminosity range was 1700 to 7700$L_{\odot}$ and the mass-loss rates were modeled to be in the range 10^{-8} to 5 x 10^{-7} $m_{\odot}$/year. The spectra were consistent with amorphous aluminium oxide dust (porous Al_2O_3).

Large-Amplitude Variables near the Galactic Centre

Because the Galactic Centre region is so heavily obscured it is very difficult to study its stellar populations. The development of large-format infrared arrays has enabled us to survey the area for its Mira variable population.

During the southern winters 1994-1997 a K-band survey was made of the central 24 x 24 arcmin^2 of the Milky Way Galaxy using the large-format PtSi camera (PANIC – see the final report by Glass, Matsumoto, Carter and Sekiguchi, (*MN* **321**, 77, 2001; errata **336**, 1390, 2002). This area was divided into 25 fields of 300 x 300 arcsec^2 each, giving some overlap. The limiting sensitivity varied from 10.0 to 11.3 mag. The long and tedious data reduction via DOPHOT and the STAR programmes written by L. Balona are described in the paper cited. Known OH/IR star positions and those of "serendipitous stars" found by Wood et al (*A&A*, **336**, 925, 1998) were searched for if they had not already turned up from the standard reduction of the survey. Light curves for ~409 stars were plotted and Fourier analysed. Some 64 of the 109 known OH/IR sources were detected.

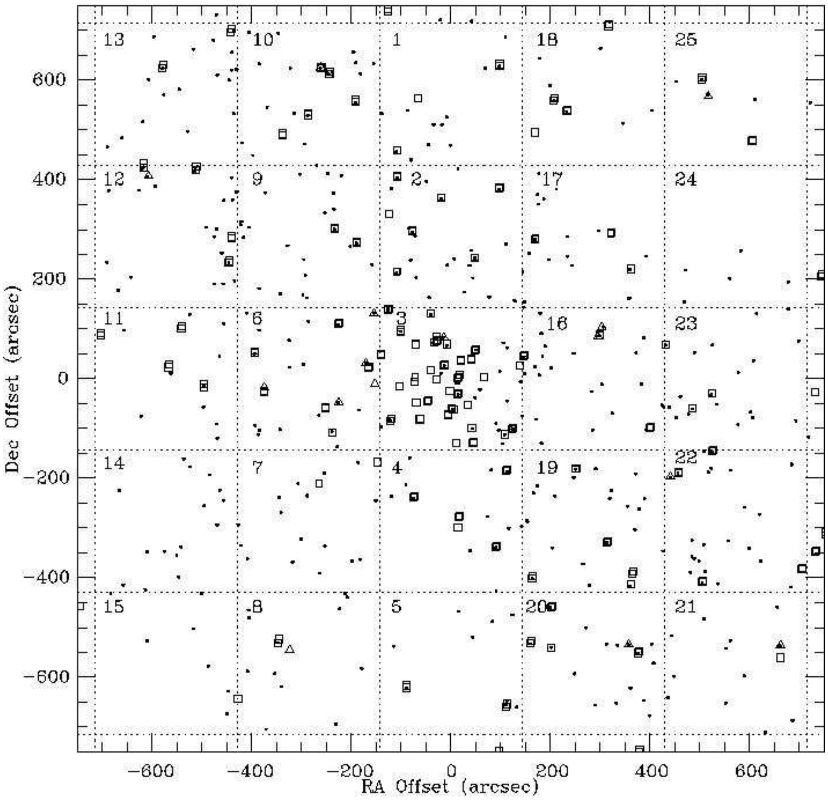


Fig 23 : Map of the survey field showing the 25 sub-fields (dotted lines). The variable stars found here are shown as dots. Known OH/IR stars are shown as squares. "Serendipitous stars" are given by triangles. There is a clear lack of detected variables in regions with high extinction, as seen for example in the Glass, Catchpole & Whitelock (MN **227**, 373, 1987*) JHK map of the area and in low-velocity ^{13}CO maps.*

Using the known K, log P relation for unreddened Miras and an assumed Galactic Centre distance, the reddenings could be estimated for stars with P < 400d. Most of these fell in the range 20< A_V<40 though any stars with reddenings in excess of A_V = 40 would have been undetectable. In adition, stars with periods longer than 400d often have shells and the K. logP relation cannot be used.

Comparisons were made with the Mira population of the Sgr I field at about 3 degrees from the Centre, from the work previously described - a sample believed to be complete. The average period found in Sgr I was 333d, while that in the GC fields was 427d, indicative of a more luminous component of younger stars. By themselves, the detected OH/IR stars averaged 524d. The amplitude distributions vs period were very similar. There are no known OH/IR stars in the Sgr I field but in the Centre OH/IR stars are moderately numerous and in addition to their longer periods tend to be of greater average amplitude than the Miras

Shorter period stars are proportionately less frequent in the Centre than in Sgr I but this may be an artifact of their generally lower amplitude and fainter magnitudes, making them harder to detect.

About 25% of the area was overlapped by the ISOGAL survey and it is interesting to note that nearly all our variables were seen on the ISOGAL maps at 7 and 15 μm. Several of the OH/IR stars that we should have seen (but did not) were detected by ISOGAL but there remained two OH/IR sources that even ISOGAL did not detect. It is presumed that these were in regions of exceptionally high reddening or were surrounded by their own exceptionally thick dust shells.

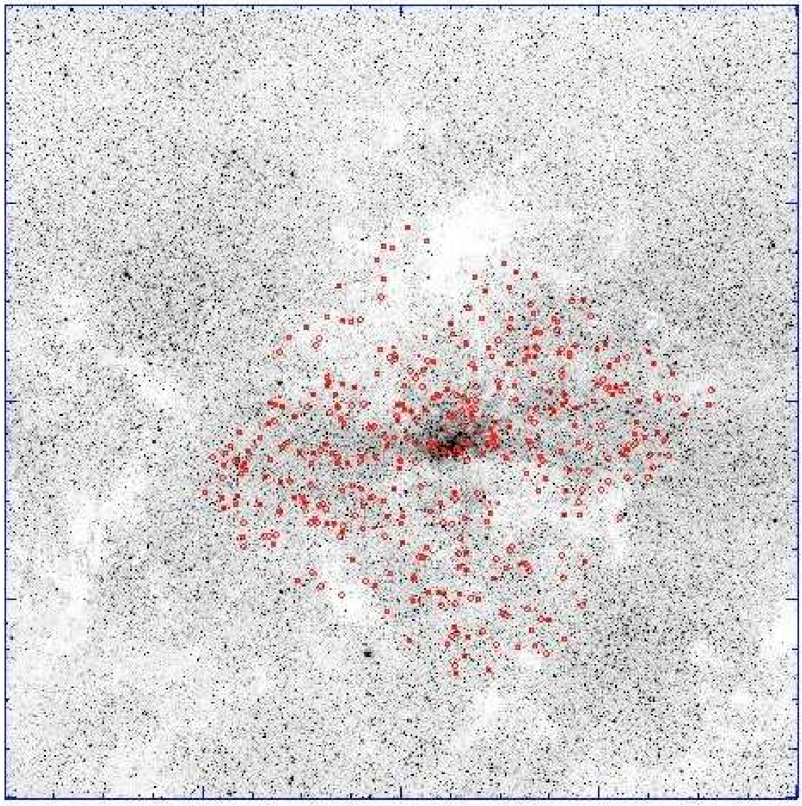


Fig24: Showing the detected LPVs superimposed on a (negative) K map of the Galactic Centre. It is noticeable that they were not seen in areas of high interstellar extinction. (From Schultheis et al A&A **495***,* 157, 2009*)*

Interstellar Extinction and LPVs in the Galactic Centre

The survey for large-amplitude variables (above), being limited to the K band, did not yield quantitative data on the extinction towards the LPVs in the Galactic Centre region and so could not be used to examine the P-L relations followed in this part of the Galaxy

Schultheis et al (*A&A*, **495**, 157, 2009) used isochrones by Marigo et al (*A&A* **482** 883, 2008) fitted to red giants and AGB stars in the Spitzer IRAC catalogue to determine the extinctions in small fields of 2 x 2 $arcmin^2$ near each of the LPVs. These are supplemented by 3.6 and 5.8μm data from the IRAC Glimpse-II survey for regions in which $A_V > 20$. In this way, at least some information was available out to $A_V = 70$. However, it should be noted that even 2 x 2 $arcmin^2$ boxes are too crude in many cases to take account of some filamentary dark clouds.

A colour-magnitude diagram [3.6] – [8.0] vs [8.0] including known LPVs and OH/IR stars could then be constructed and compared with the Marigo et al isochrones.

The de-reddened Glimpse II (IRAC) results for the Galactic Centre Miras were plotted on magnitude, log P diagrams together with a group of AGB variables from the LMC by Cioni et al (*A&A* **347**, 945, 2001) that also appear in the IRAC surveys. However, the relations fitted to these do not agree well with what was found by Glass et al (*MN 395*, L11, 2009; see above) for NGC6522 and the LMC. It can be seen though that for the Cioni et al LMC sample, if stars with periods longer than ~400d are ignored, the agreement is reasonable.

As to the Galactic Centre LPVs, most have periods in excess of 400d and almost certainly have strong mass-loss, which affects their longer-wavelength colours to such an extent that they cannot be expected to follow the magnitude-period relations defined by stars with p < 400d.

Better (though not perfect) agreement with the Glass et al NGC6522 and LMC mid-IR magnitude, log P relations was found by Matsunaga et al (2009, see below). The major difference here is that they limited their discussion to variables with p < 350d.

IRSF Survey of Miras towards the Galactic Centre

A much improved survey, when compared to that of Glass et al (2002), was conducted by Matsunaga et al (2009) of a 20 x 30 $arcmin^2$ field towards the Galactic Centre, using the IRSF telescope and Sirius camera. The limit of their survey was about 1 mag deeper at K and it included J and H information in 143 cases, enabling the reddening to individual stars with periods in the range 100-350d to be estimated from their colours. The reddenings so determined ranged from A_K = 0.15 to > 4; for higher reddenings no estimate could be made.

The distance to the Galactic Centre was estimated at 8.24±0.08 (statistical) ±0.42 (systematic) kpc, assuming a d.m. to the LMC of 18.45 mag

They also extracted mid-IR IRAC magnitudes for their sample and could determine magnitude-period relations at these wavelengths, in broad agreement with those of Glass et al (2009 above) that were based on the LMC and Sgr I fields.

Search for SiO masers among the Galactic Centre LPVs

The Miras in the Galactic Centre can be identified in many cases with OH/IR and SiO maser sources, so that their radial velocities can be determined from radio spectra even if they are invisible due to absorption by interstellar dust. SiO masers are more certain to be associated with late-type stars than the more-widely studied OH ones as 1612 OH masers can also arise from star-forming regions.

In the first report of a SiO maser detection programme in which I participated, Imai et al (*PASJ*, **54**, L19, 2002) searched 134 of the variables in Glass et al (2001) for SiO maser emission, detecting 79 of them.

Deguchi et al (*PASJ*, **56**, 261, 2004) extended the sample to 396 Large – Amplitude Variables, of which 180 were detected in SiO. The detection percentage reaches 80% for P > 500d. The detection rate for SiO in LPVs with periods in the range 200-500d is triple that of OH. The longitude-velocity diagram of the SiO sources in addition resembles that of OH/IR sources, with some subtle variations perhaps indicative of population differences.

The SiO detection rate in the 24 x 24 $arcmin^2$ field is similar to that for OH/IR sources and their longitude-velocity diagrams of are also similar. These sources were thus shown to be similar in nature to the IRAS-detected Large-Amplitude Variables of the Inner Bulge.

The molecular line observations show that the nuclear disc within 0.5d from the Centre is rotating at ~190km s^{-1} per degree, while out to 3° the rate is ~20km s^{-1} per degree.

The velocity data with the assumption of a spherically symmetric stellar density distribution could be used to estimate the mass of the central black hole of 2.7 (±1.3) x 10^6 $M_\odot$ and the mass within 30 pc to be 6.5 (± 0.7) x 10^7 $M_\odot$.
[Current estimate of the mass of Sgr A* = 4.3 x 10^6 $M_\odot$].

In a further SiO search (Deguchi et al *PASJ*, **56**, 765), this time concentrating on IRAS objects selected by colour as likely to be AGB stars, in -10°< *l* <40°**,** |b| < 3°, 254 SiO masers out of 401 candidates were found. The rotation speed vs *l* was found to be 21 (±13) km s^{-1} kpc^{-1} between 1 and 1.5 kpc from the Sun and for 5.5 to 7 kpc it was up to 60 km s^{-1} kpc^{-1}. These IRAS sources could be identified in the 2MASS JHK survey and their distances could be estimated roughly using the assumption that they are all of M6III type and that they are reddened according to a standard model (Unavane et al, *MN* **295**, 119, 1998).

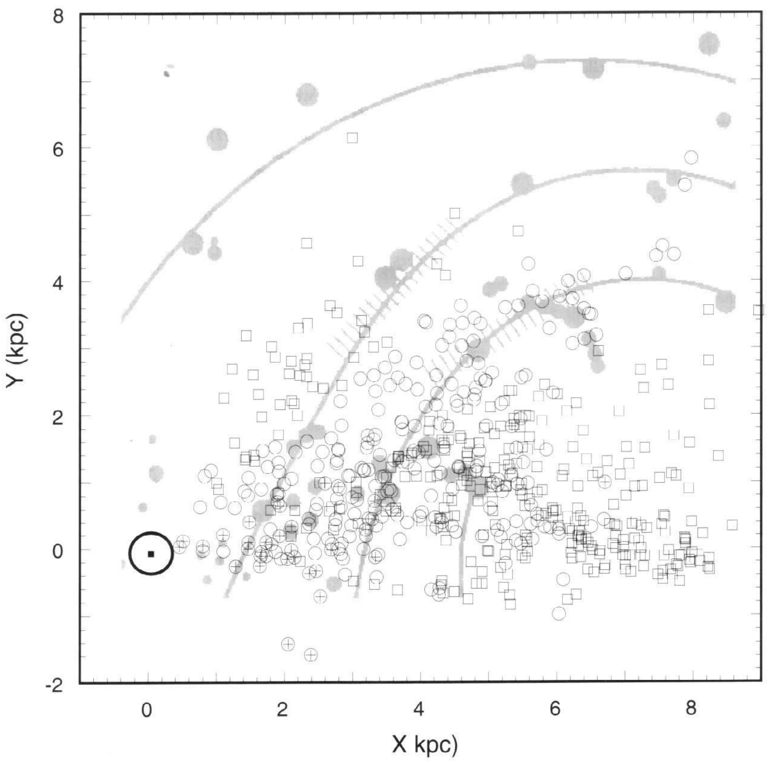


Fig 25: The first quadrant of the Galaxy mapped in known SiO sources (from various papers). There are conspicuous features, such as the Bulge Bar and one at (3, 0.5), corresponding to a dense area of HII regions in the Molecular Ring.

The *l*-v diagram for the SiO and OH masers shows similarity to that for the molecular gas. There are certain "forbidden" regions, indicative of a bar-like potential.