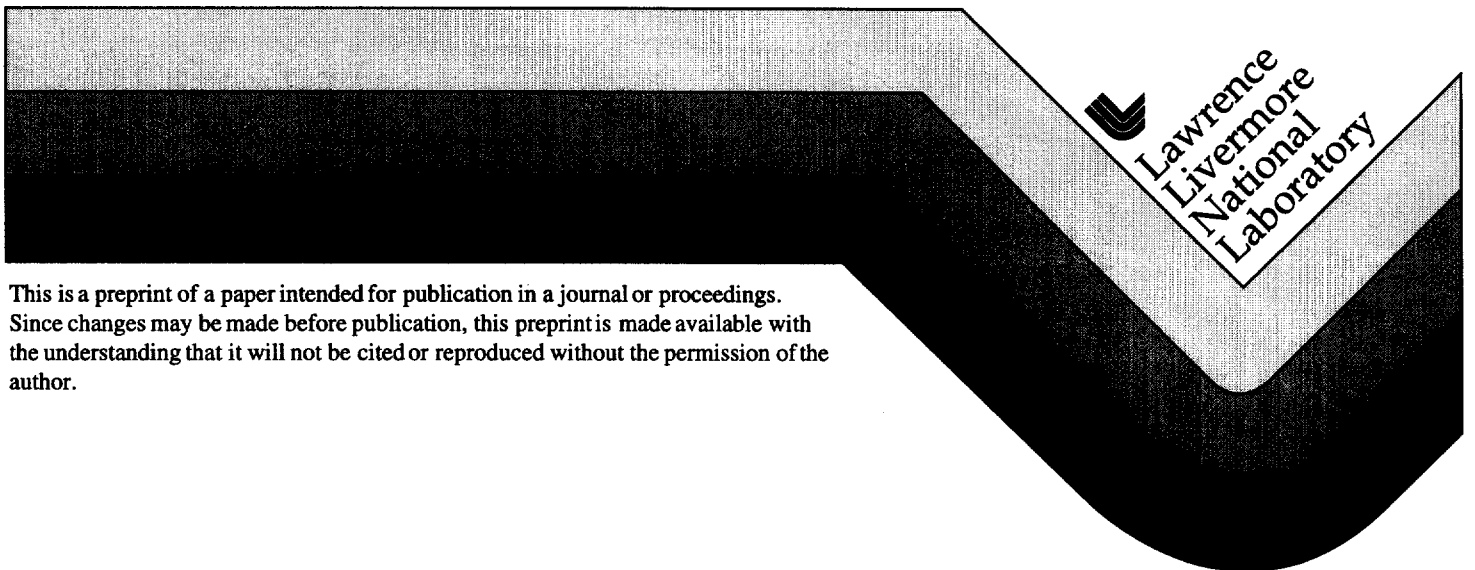# Pulsating Variable Stars in the MACHO Bulge Database: The Semiregular Variables

D. Minniti, C. Alcock, R.A. Allsman, D. Alves, T.S. Axelrod, A. Becker,
D.P. Bennett, K.H. Cook, K.C. Freeman, K. Griest, M.J. Lehner, S. Marshall,
B.A. Peterson, M.R. Pratt, P.J. Quinn, A.W. Rodgers, C.W. Stubbs,
W. Sutherland, A. Tomaney, T. Vandahei and D.L. Welch

DISCLAIMER

Pulsating Variable Stars in the MACHO Bulge database: The Semiregular Variables

D. Minniti[1], C. Alcock, D. Alves, K. Cook, S. Marshall

Lawrence Livermore National Laboratory

R. Allsman, T. Axelrod, K. Freeman, B. Peterson, A. Rodgers

Mount Stromlo and Siding Springs Observatory

K. Griest, T. Vandehei, A. Becker, C. Stubbs, A. Tomaney

University of California San Diego, University of Washington

D.Bennett, M. Lehner, P.Quinn

Notre Dame, Sheffield University, European Southern Observatory

M. Pratt, W.Sutherland, D.Welch

MIT, Oxford University, McMaster University

(The MACHO Collaboration)

Abstract. We review the pulsating stars contained in the top 24 fields of the MACHO bulge database, with special emphasis on the red semiregular stars. Based on period, amplitude and color cuts, we have selected a sample of 2000 semiregular variables with $15 < P < 100$ days. Their period-luminosity relation is studied, as well as their spatial distribution. We find that they follow the bar, unlike the RR Lyrae in these fields.

1. Introduction

Current microlensing experiments (MACHO, Alcock et al. 1997; EROS, Aubourg et al. 1995; OGLE, Udalski et al. 1993; DUO, Alard 1996) have produced exquisite light curves of variable stars as byproducts. These thousands of light curves allow us to address advanced questions regarding stellar evolution, pulsational physics, the distance scale and Galactic structure, which would in turn aid in the interpretation of microlensing. This paper reports on the MACHO pulsating variable stars, with emphasis on the semiregular variables in the bulge, which have not been previously analyzed. The LMC counterparts are discussed in this book by Alves at al. (1998), and a list of references regarding

---

[1]e-mail: dminniti@llnl.gov

other variable stars in the MACHO database can be found in our web page at **http://wwwmacho.mcmaster.ca/**. This paper is part of a systematic study of the structure of the inner Milky Way using different distance indicators contained in this database (Minniti et al. 1996, 1997).

A description of the MACHO system is given by Cook et al. (1995, 1996). Briefly, the 1.3m telescope at MSSSO obtains nightly images of several bulge, LMC, or SMC fields in two passbands simultaneously. These images are photometered on-line, and later calibrated to produce accurate V and R magnitudes. Variable stars are also identified automatically, and their light curves are phased using a super-smoother algorithm (Cook et al. 1995).

The period-amplitude diagram of 40000 periodic variables in the top 24 MACHO fields from the 1993 season is shown in Figure 1. These variables have periods $0.1 < P < 100$ days. Stars with periods longer than 100 days (e.g. Miras) have not been phased yet, although our light curves in the bulge contain typically 700 points over a 5-year baseline. The presence of RR Lyrae type ab at $0.4 < P < 1$ day and semiregulars at $15 < P < 100$ is evident. In addition, there is a large number of eclipsing binaries with $A < 1$, spanning a wide range of periods. The binaries with shorter periods overlap in the diagrams of Figure 1 with the RR Lyrae type c.

The nightly observations introduce aliasing when phasing the light curves of variable stars. These aliased periods with $P = 1/n$ days (with $n = 1, 2, ...$) are seen in Figure 1. To eliminate aliases, we demand that the periods in both bands are the same to within a few percent, i.e. $P_V = P_R \pm 2\%$.

2.   Selection of Pulsating Variable Stars

Clearly, the visual inspection of the light curves of 40000 bulge variables would be time consuming. Fortunately, the automatic classification of variable stars can be very much improved having observations in two different passbands. The discrimination between eclipsing and pulsating variables in this database is most easily done using the amplitude ratios. Most pulsating variable stars have $A_R < 0.8 \ A_V$, while the light curves of most eclipsing binaries have $A_V = A_R$.

Figure 2 shows the same diagrams as Figure 1, but containing only pulsating variables, simply selected using $P_V = P_R \pm 2\%$ and $A_R < 0.8 \ A_V$. These diagrams look much cleaner, showing the different families of pulsating stars. These are δ Scuti stars, with $P < 0.2$ days, RR Lyrae stars type c, with $0.2 < P < 0.4$ days, RR Lyrae type ab, with $0.4 < P < 1.1$ days, and semiregular variables, with $15 < P < 100$ days.

2.1.   The RR Lyrae Stars

The RR Lyrae in the MACHO bulge database were studied by Minniti et al. (1996). They found that (1) they do not follow the bar in the inner regions, (2) they are very concentrated, (3) the fainter RR Lyrae belong to the Sgr dwarf galaxy, located behind the bulge, and (4) the period-amplitude diagram differs from that of the LMC, with larger fraction of RRc/RRab types.

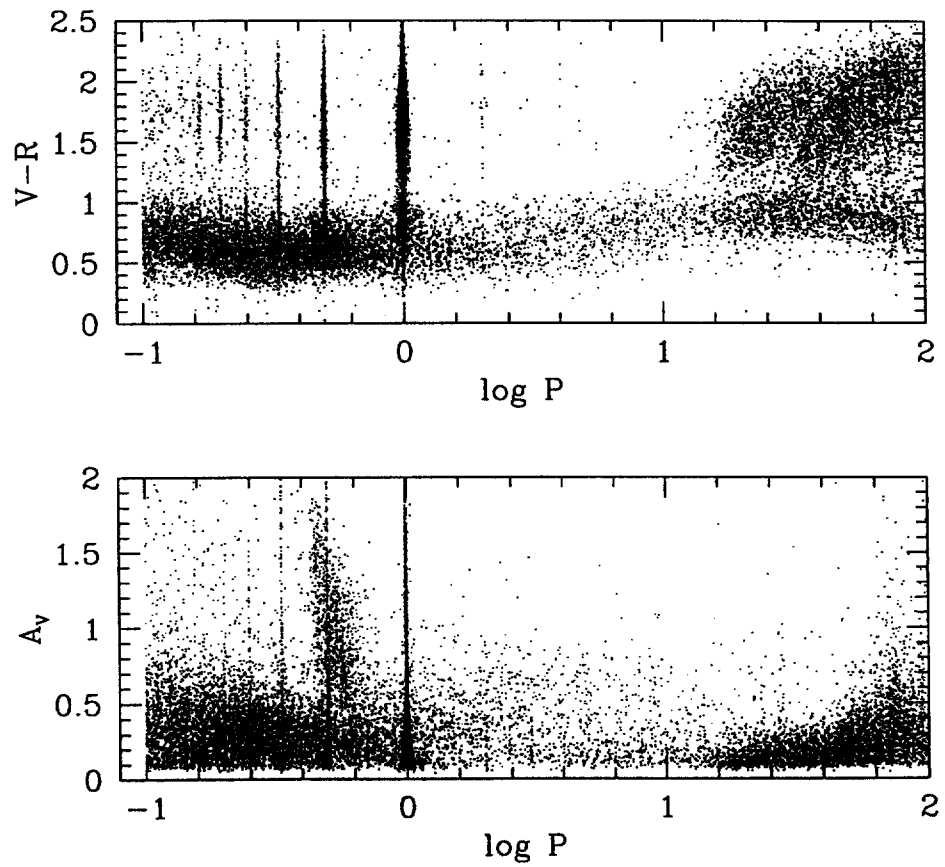Figure 1.   Period-amplitude and period-color diagrams for periodic bulge stars with $0.1 < P < 100$ days. The vertical groups of points at submultiples of 1 day are due to aliasing.
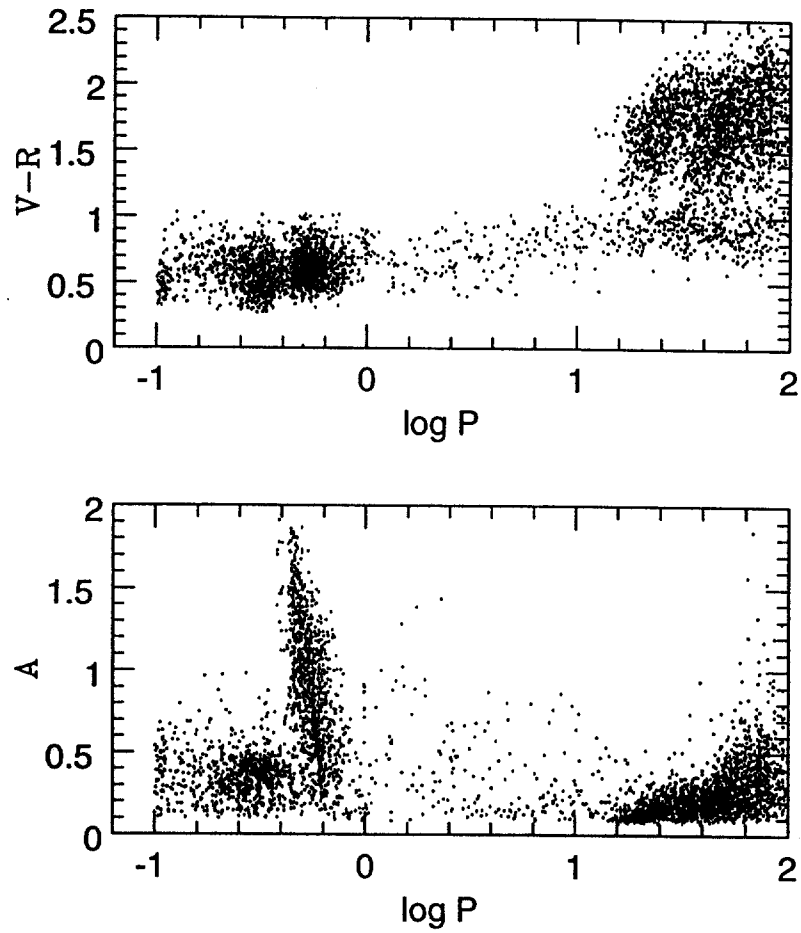
Figure 2. Same as Figure 1, showing only bulge pulsating stars with
$0.1 < P < 100$ days. There are, in order of increasing $log\ P$, δ Scutis,
RR Lyrae type c, RR Lyrae type ab, and semiregular variables.

4

2.2. The δ Scuti Stars

The large amplitude δ Scuti stars in the MACHO bulge database were studied by Minniti et al. (1997). They found that (1) these stars belong to the bulge, and not to the disk, (2) they are most likely bulge blue stragglers, (3) they are potentially good distance indicators, and (4) they are also very concentrated.

2.3. The Cepheid Stars

Cepheid variable stars are very numerous in the Magellanic Clouds (Alcock et al. 1995, Welch et al. 1996, Sasselov et al. 1997). Note, however, that there are very few Cepheids candidates in the bulge database (Figure 2). These few Cepheids, with $1 < P < 15$ days, and $A < 1.5$, belong to the disk of our galaxy. The bulge population is too metal rich and too old to contain such stars.

3. The Semiregular Variables

The rest of this paper will be devoted to bulge semiregular variable stars. Semiregulars are red giant pulsators, more numerous that Miras, but with smaller amplitudes and shorter periods. They have, however, been less well studied than the Miras (see Gautschy & Saio 1996 for a review). Figures 3 and 4 show the MACHO light curves of 4 such stars, illustrating why they are called semiregular variables.

As mentioned above, pulsating bulge variables are selected using cuts in periods and amplitudes: $P_V = P_R \pm 2\%$ and $A_R < A_V$ 0.8. The bulge semiregular variables are chosen using farther cuts in periods, colors and amplitudes. We use $P > 15$ days to discard shorter period pulsators (δ Scuti, RR Lyrae, Cepheids, etc), $P < 100$ days to eliminate variables with longer periods (LPVs, Miras), $V - R > 1.0$ to discriminate from bluer variables, $A_V > 0.1$ to ensure good quality, $A_V < 1.0$ to avoid the occasional Mira or LPV that has been wrongly phased. These cuts produce a sample of 2000 semiregular variables in the bulge.

Note that the periods used in this paper were determined from the 1993 data only. The long term period stability of these stars in not known. Some of these periods may change from season to season, as a result of the semiregular behavior of these variables. Multiple and variable periods have been observed (e.g. Lebzelter et al 1995) However, the selection criteria applied to these data guarantees that during at least one season, the periods measured using both passbands agree.

The selected sample of 2000 bulge semiregulars is plotted in Figure 5. The onset of pulsation occurs at $P = 15$ days, with low amplitudes, $A = 0.1$ mag. We have not considered variables with $A < 0.1$ mag, so there may be more lower amplitude semiregulars with periods $P < 15$ days. The amplitudes increase with increasing periods, but they are not larger than 1 magnitude.

Figure 5 shows that there are two sequences of semiregulars in the bulge. These sequences are more clearly seen in the period-color diagram, where a clear separation is obtained applying the cuts $V - R > 2.5 \ logP - 2.12$, and $V - R < 2.5 \ logP - 2.12$. These sequences have stars with with $16 < P < 40$ days, and $32 < P < 100$ days, and both sequences have mean amplitudes increasing with period. Red giants evolve upwards on the giant branch, and
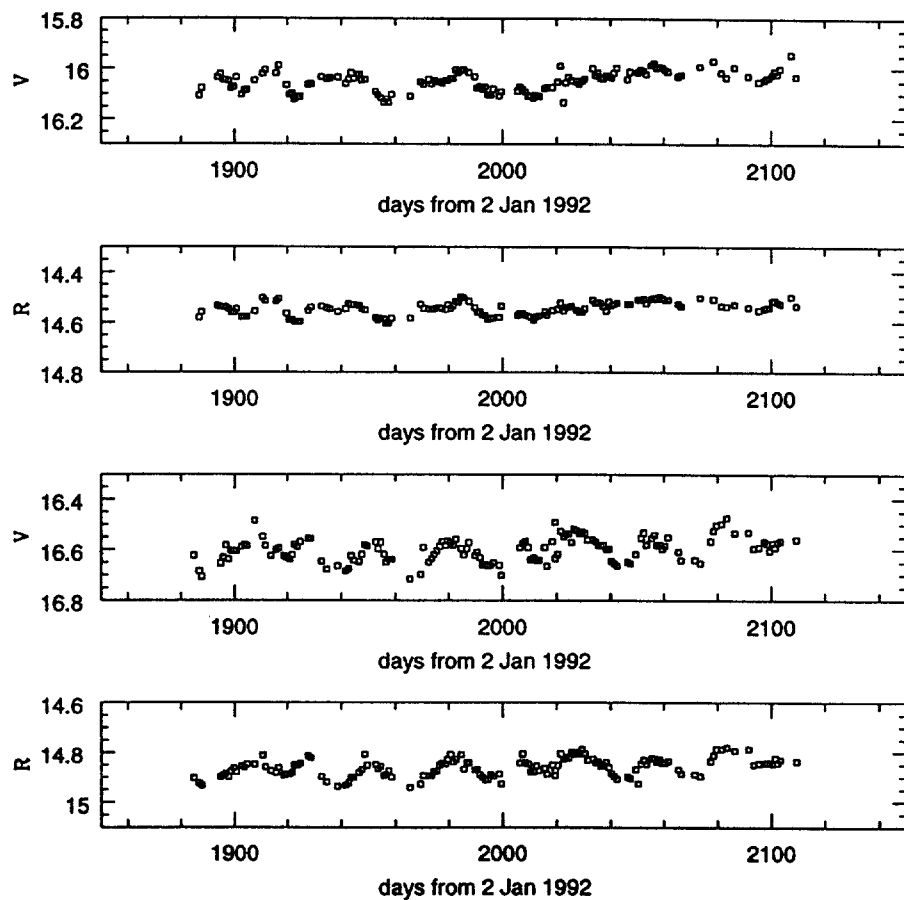
5

Figure 3.   Observed V and R light curves for the 1997 season of two bulge semiregular variables. These correspond to the shorter period sequence: Macho 119.19829.52, with $P = 21.5$ days (top panels), and Macho 113.19193.54, with $P = 26.0$ days (bottom panels).
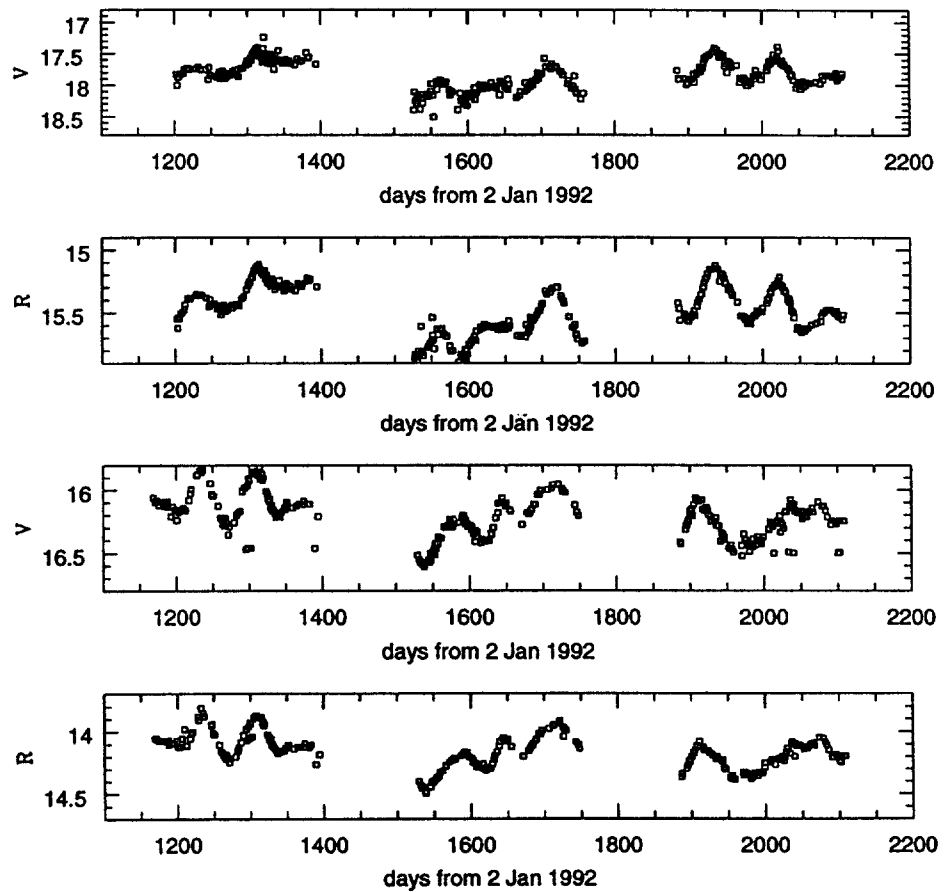
Figure 4.   Observed V and R light curves for the 1995, 1996 and 1997 seasons of two bulge semiregulars. These belong to the longer period sequence: Macho 119.20096.26, with $P = 72.5$ days (top panels), and Macho 101.21438.88, with $P = 80.6$ days (bottom panels).
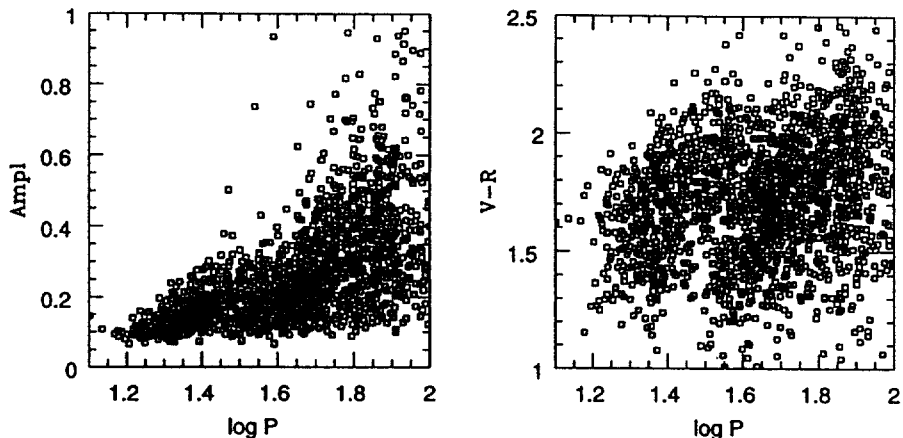
7

Figure 5. Left panel: Period-amplitude diagram for 2000 bulge semiregular variables. Right panel: Period-color diagram. Note the two groups with short and long periods.

the semiregulars with $32 < P < 100$ days should be more evolved than the ones with $16 < P < 40$ days. Indeed, the long period semiregulars tend to be redder and brighter in the mean than the short period ones. Similar sequences, although much tighter, are seen in the MACHO LMC database (e.g. Cook et al. 1996, Alves et al. 1998). We speculate that these sequences represent stars pulsating in different modes, as predicted by Wood & Cahn (1977). These sequences provide a more natural classification scheme than the traditional SRa and SRb classes. The relation of these sequences to the longer period Mira variables has not been studied yet. Unlike these longer period variables, semiregulars with $P < 100$ days do not necessarily have circumstellar shells (Kerschbaum & Hron 1996). Previous studies have shown that in the Milky Way disk, the kinematics and scale-heights of the semiregular variables are similar to these of the Miras (Jura & Kelinmann 1992), suggesting that they trace similar populations. In particular, a possible extension (if any) of the Mira period-luminosity relations into the shorter periods covered by the semiregular variables could be useful for the determination of the extragalactic distance scale.

3.1. The Color-Magnitude Diagrams

Figure 6 shows the location of the 2000 semiregular variables in the color-magnitude diagram. Overplotted are 10000 stars in Baade's window, a typical bulge field, showing the disk main sequence at $V - R \sim 0.5$, the bulge red giant branch at $V - R \sim 0.7 - 1.0$, and the red giant branch clump at $V = 17$, $WV = 14$, $V - R \sim 0.9$. The reddening independent magnitude WV is defined as $WV = V - 3.97(V - R)$. These diagrams illustrate that the semiregular variables are located in the bulge, and not in the foreground disk. Among the reddest stars in the bulge, they are oxygen rich giants located at the tip of the bulge red giant branch. The semiregulars lie along the direction of the reddening vector in the color-magnitude diagram, because absorption is large and non-uniform in the observed bulge fields. The MACHO bulge images with exposure times
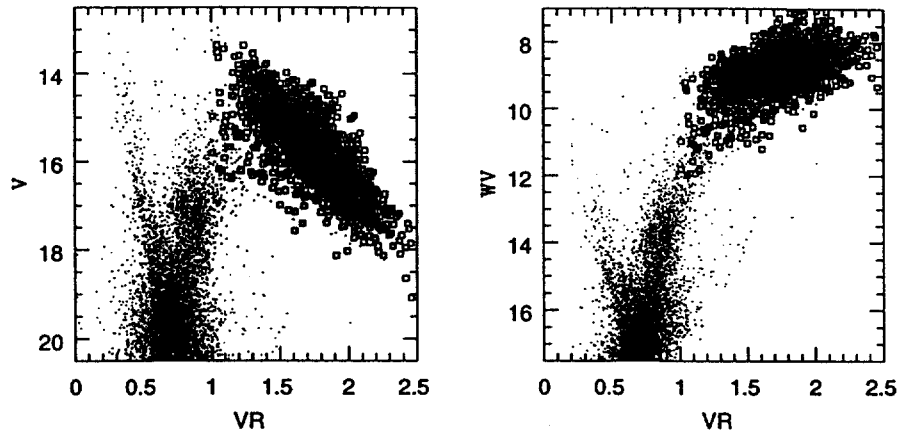
Figure 6.   Color-magnitude diagrams of 2000 bulge semiregular variables (squares), overplotted with 10000 stars in Baade's window, a typical bulge field (points). Left: V vs $V - R$. Right: Reddening independent magnitude WV vs $V - R$ diagram.

of 150 sec saturate at $V \sim 13$, so a few of the brightest stars may have been missed.

3.2.   The Period-Luminosity Relation

Semiregular variables are bright, easy to detect, and very numerous in old stellar populations. They are fainter than Miras, but more numerous. They are brighter and more numerous than RR Lyrae and δ Scuti stars. Their luminosity is roughly comparable with Cepheids, which are bluer, but they are much more numerous. It would then be important if they could be used as distance indicators. Is there a period-luminosity relation for these stars? This question can be addressed with the MACHO bulge and LMC database, that contains thousands of semiregulars, located at about the same distance.

Figure 7 shows the period-luminosity plane for these variables. The spread in the V magnitudes is due to the bulge line-of-sight depth, and to differential reddening. Due to this scatter, no clear dependence of V with P is observed. We then use the reddening independent magnitudes, which show smaller spread, solely due to the bulge line-of-sight depth, and also a clearer separation between the two sequences.

There appears to be another sequence about 2 magnitudes fainter, containing fewer stars than the two principal sequences. This third sequence is seen in the right panel of Figure 7 for $P > 30$ days, and $10 < WV < 12$. These stars could be semiregulars in the Sgr dwarf galaxy, located behind the bulge, at a distance of 25 kpc from the Sun (see Alard 1996 and Alcock et al. 1997). However, a similar sequence may also be present in the LMC, so the identification and interpretation remains unclear.

The left panel of Figure 7 shows the dependence of luminosity on the period of the stars. The inferred period-luminosity relation for the whole sample of
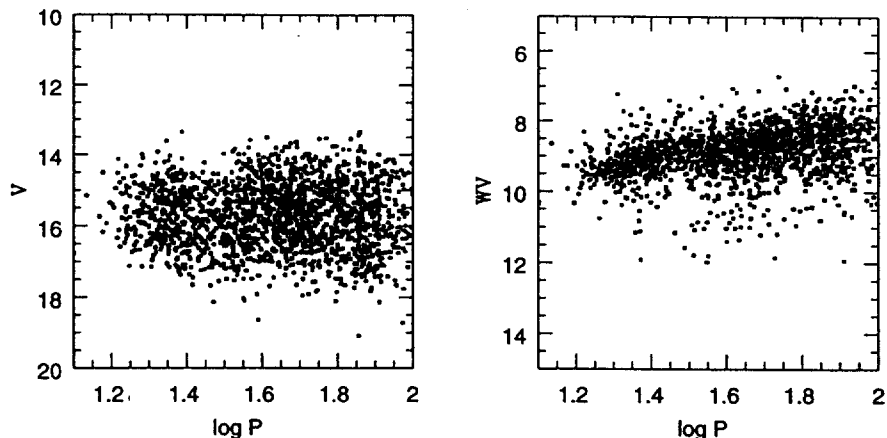
9

Figure 7. Left panel: Period-V magnitude relation for 2000 semiregular variables. Right panel: Period-WV magnitude relation.

semiregulars with $15 < P < 100$ days is:

$$WV \approx -1.78 \ log \ P + 11.56$$

However, dividing into two groups, presumably representing variables pulsating in different modes, yields the following preliminary period-luminosity relations:

$$WV \approx -3.33 \ log \ P + 13.66 \quad (15 < P < 40 \ d)$$

$$WV \approx -3.33 \ log \ P + 14.47 \quad (30 < P < 100 \ d)$$

3.3. The Spatial Distribution

We have computed the mean reddening independent magnitudes of the semiregulars for each of the top 24 MACHO bulge fields. These mean magnitudes are plotted in Figure 8. This figure shows that the bulge semiregular variables trace the bar: the semiregulars away from the Galactic minor axis appear to be brighter, and therefore closer, than the ones along the minor axis. The dependence of the semiregulars mean V and R magnitudes on Galactic longitude is similar to that of WV shown in Figure 8, with somewhat larger scatter due to variable reddening.

The trend seen in Figure 8 follows that of the bulge clump giants (Stanek et al. 1996, Alcock et al. 1997), and of the Mira variables (Whitelock 1993), which also clearly show a barred distribution. This suggests that the bulk of the semiregular variables are metal-rich, because metal-poor stars (such as RR Lyrae) do not follow the bar (Alcock et al. 1997).

3.4. Bulge Semiregular Variables: New Challenges

Past studies of semiregular variables have not been as detailed as those of other pulsating stars like δ Scuti, RR Lyrae, Cepheids or Miras. This was partly due to the semiregular nature, which makes it necessary to have observations
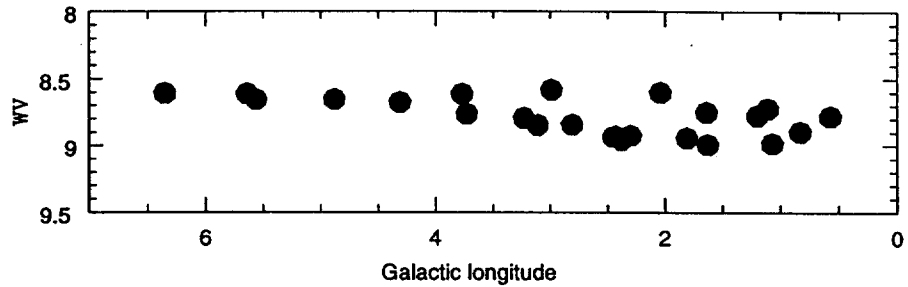
10

Figure 8. Mean reddening independent magnitude for bulge semiregular variables in each of the top 24 MACHO fields *vs* Galactic longitude. This figure shows that these stars follow the barred distribution seen in the clump giants and other tracers.

over extended periods of time. Nonetheless, carefully selected samples of these variables can be used as distance indicators, having the advantage of being more numerous than some of these other variables. We have shown that there is a period-luminosity relation for semiregular variables in the bulge, and that they can be used as tracers of the structure of the inner Milky Way. In particular, we find that they follow the inner bar, like clump giants, and Mira variable stars.

There are, however, several questions that remain open for further study concerning the bulge semiregular variables:

– How do they relate to the Mira-type variables?
– What are their pulsation modes?
– What is their long term pulsational stability?
– Is there a metallicity dependence of their period-luminosity relation?

The current and future microlensing experiments would help solve these issues in the near future. A complete inventory of semiregular variables would also aid in the selection of real microlensing events in more distant galaxies using difference image photometry (e.g. Columbia-VATT, Tomaney & Crotts 1997; AGAPE, Ansari et al. 1997).

References

Alard, C. 1996, ApJ, 458, L17
Alcock, C. et al. (The MACHO Collaboration), 1995, AJ, 109, 1653
Alcock, C. et al. (The MACHO Collaboration), 1997, ApJ, 474, 217
Alcock, C. et al. (The MACHO Collaboration), 1998, ApJ, in press

11

Ansari, R., et al. (The AGAPE Collaboration), 1997, A&A, 324, 843

Alves, D., et al. (The MACHO Collaboration), 1998, this book

Aubourg, E., et al. (The EROS Collaboration), 1995, A&A, 301, 1

Beaulieu, J.-P., et al. (The EROS Collaboration), 1997, A&A, 321, L5

Cook, K., et al. (The MACHO Collaboration), 1995, in ASP No. 83, p. 221

Cook, K., et al. (The MACHO Collaboration), 1996, in "Variable Stars and the Astrophysical Returns of Microlensing", eds. R. Ferlet et al. (Editions Frontieres: Paris), p. 17

Gautschy, A., & Saio, H. 1996, ARA&A, 34, 551

Jura, M., & Kleinmann, S. G. 1992, ApJS, 79, 105

Kerschbaum, F., & Hron, J. 1996, A&A, 308, 489

Lebzelter, T., Kerschbaum, F., & Hron, J. 1995, A&A, 298, 159

Minniti, D., et al. (The MACHO Collaboration), 1996, in "Variable Stars and the Astrophysical Returns of Microlensing", eds. R. Ferlet et al. (Editions Frontieres: Paris), p. 257

Minniti, D., et al. (The MACHO Collaboration), 1997, in IAU Coll. 189 on "Fundamental Stellar Properties: The Interaction Between Observation and Theory", eds. T.R. Bedding et al. (Kluwer: Dordrecht), p. 293

Percy, J. R., et al. 1996, PASP, 108, 139

Sasselov, D., Beaulieu, J.-P., et al. (The EROS Collaboration), 1997, A&A, 324, 471

Stanek, K. Z., et al. (The OGLE Collabotarion), 1994, ApJ, 429, L73

Tomaney, A. B., & Crotts, A. P. S. 1997, AJ, 112, 2872

Udalski, A., et al. (The OGLE Collabotarion), 1993, Acta Astr., 43, 69

Vassiliadis, E., & Wood, P. R. 1994, ApJS, 92, 125

Welch, D., et al. (The MACHO Collaboration), 1996, in "Variable Stars and the Astrophysical Returns of Microlensing", eds. R. Ferlet et al. (Editions Frontieres: Paris), p. 205

Whitelock, P., 1993, in IAU Symp. 153 on "Bulges of Galaxies", eds. H. Dejonghe & H. Habing (Kluwer: Dordrecht), p. 39

Wood, P., & Cahn, 1977, ApJ, 211, 499