BULGE δ SCUTI STARS IN THE MACHO DATABASE

D. MINNITI[1], C. ALCOCK[1], D.R. ALVES[1], T.S AXELROD[2], A.C BECKER[3], D.P. BENNETT[4], K.H. COOK[1], K.C. FREEMAN[2], K. GRIEST[5], M.J. LEHNER[5], S.L. MARSHALL[1], B.A. PETERSON[2], P.J. QUINN[6], M.R. PRATT[3], A.W. RODGERS[2], C.W. STUBBS[3], W. SUTHERLAND[7], A. TOMANEY[3], T. VANDEHEI[5], D. WELCH[8],

[1]*LLNL;* [2]*MSSSO;* [3]*U. Washington;* [4]*Notre Dame;* [5]*UC San Diego;* [6]*ESO;* [7]*Oxford U.;* [8]*McMaster U.;*

1. Introduction

We describe the search for δ Scuti stars in the MACHO database of bulge fields. Concentrating on a sample of high amplitude δ Scutis, we examine the light curves and pulsation modes. We also discuss their spatial distribution and evolutionary status using mean colors and absolute magnitudes.

The 61" telescope at Mt. Stromlo Observatory observes once a night several bulge or LMC fields in two bandpasses. While the MACHO system is optimized for microlensing, it has also had great success detecting variable stars (Cook et al. 1995). We have searched for δ Scuti stars in the bulge fields (these variable stars are beyond the detection limit in the LMC fields). The δ Scutis have very short periods, typically between 1 hr and 6 hr (e.g. Breger 1995, Rodriguez et al. 1994), which may be challenging using a once-a-day observing routine. Amazingly enough, the light curves of δ Scu stars phase very well for periods as short as 0.08 days. Because subsequent observations are separated by 5-15 pulsation periods, the phases are randomized, giving a rather uniform light curve coverage. Also, because we have so many datapoints per star ($\sim$ 500 over four seasons), aliasing is not a significant problem. The quality of the light curves (Figure 1) say more than a thousand words...

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The δ Scu stars are selected using the period-amplitude diagram for all stars with $P < 0.20^d$, and amplitudes $A_V > 0.1$ mag in the MACHO blue band, taking for comparison the catalogue of Rodriguez et al. (1994). We demand that $P_V = P_R$ to within 2%. The δP criterion implies that we keep mainly the variables that have good quality light curves, and that are not multi-mode pulsators. The lower cut in the amplitudes is imposed to secure good data, even though small amplitude δ Scu stars will also be neglected. We also demand that $A_R < 0.8 A_V$, in order to eliminate eclipsing binaries which have $A_V \approx A_R$. Finally, the identification of these large amplitude δ Scu candidates is confirmed by visual inspection of the light curves.

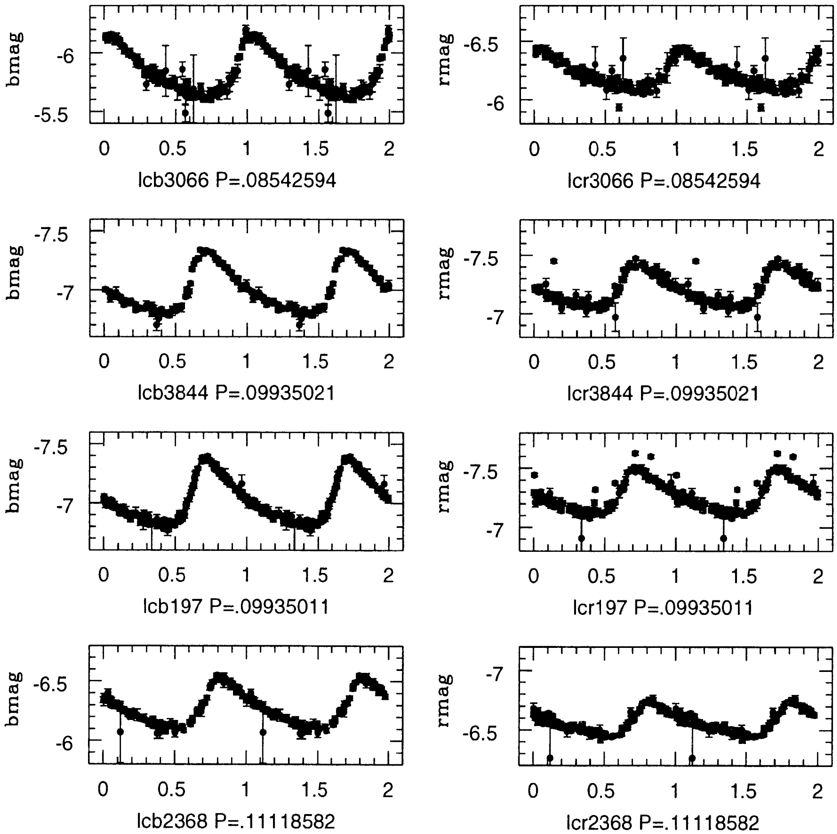

Fig. 1 - Typical blue (left panels) and red (right panels) δ Scu light curves.

Thus, we do not consider the low amplitude, the short period, and most double or multi-mode δ Scu stars. Even though the sample is incomplete, it is adequate to examine the extension of the existing P-L-Z relations into the metal-rich domain, and to determine the evolutionary status of these stars in the bulge.

2. Light Curves: Fundamental, 1st Overtone, or 2nd Overtone?

The light curve shapes of the δ Scu stars in our sample are similar to short-period versions of RR Lyrae type ab and type c variables. Theoretical light curves for δ Scu stars pulsating in the fundamental, first overtone, and second overtone modes have been recently computed by Bono et al. (1997). In particular, they predict for the first time the occurrence of stable second overtone pulsators. While a more detailed exploration of the full parameter space is needed, these models (Bono et al. 1997, their Figures 3–7) reproduce the observed light curves of our sample very well.

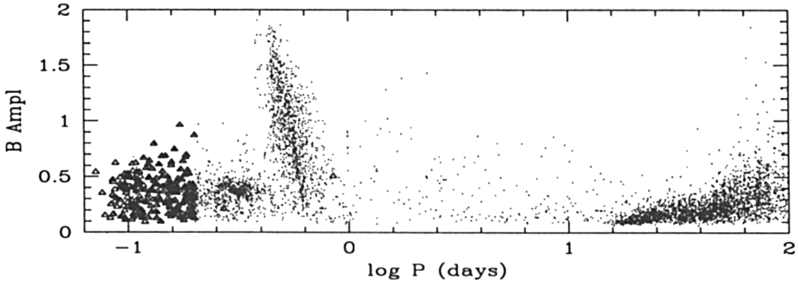

Fig. 2 - Period-amplitude diagram for pulsating bulge variables with $P < 100^d$. The δ Scu are plotted with triangles. RR Lyrae stars type ab, c, and e are also seen at $log\ P \approx -0.25$, -0.5, and -0.6 days, respectively.

Few fundamental δ Scu pulsators would be included in the sample, since these would have $P > 0.12^d$ and $A \leq 0.1$ mag. Based on these periods and amplitudes, it appears that the majority of the sample stars would be second overtone pulsators, with a few first overtone pulsators.

Bono et al. (1997) find that, contrary to different RR Lyrae pulsators, the second overtone δ Scu pulsators show larger amplitudes, in spite of having smaller periods than the first overtone or the fundamental pulsators. This is in direct contradiction with the assumption that, like RR Lyrae and Cepheid stars, the higher modes have lower amplitudes (e.g. McNamara 1995). Furthermore, the theoretical light curves of Bono et al. (1997) show that fundamental δ Scu pulsators should have sinusoidal light curves, and that first or second overtone pulsators should have asymmetric light curves. This also is in direct contradiction with the assumption that, like RR Lyrae stars, the asymmetric light curves are indicative of fundamental mode pulsation, with sinusoidal light curves present in first –and maybe also in second– overtone pulsators (e.g. Nemec et al. 1995, McNamara 1995).

3. The Evolutionary Status of δ Scu Stars in the Bulge Fields

The reddening in the bulge fields is very inhomogeneous. From the VR photometry it is convenient to use the reddening independent magnitude

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W_V, defined as $W_V = V - 3.97 \times (V - R)$, which assumes a standard extinction law for the bulge fields. Most of the δ *Scu* stars in our sample belong to the Galactic bulge; their magnitudes peak at $W_V = 15.9$, which places them at about 8 kpc.

The δ Scu are core hydrogen burning stars located inside the instability strip, on the main sequence or just above the main sequence (Breger 1995, Rodriguez et al. 1994). For a population older than about 10^{10} yr, the instability strip lies bluewards of, and it is brighter than the main sequence turn-off. Thus, in old populations, the pulsating variables in the instability strip must occur in blue stragglers. It is now well established that SX Phe stars in globular clusters are blue stragglers (Nemec et al. 1994, 1995).

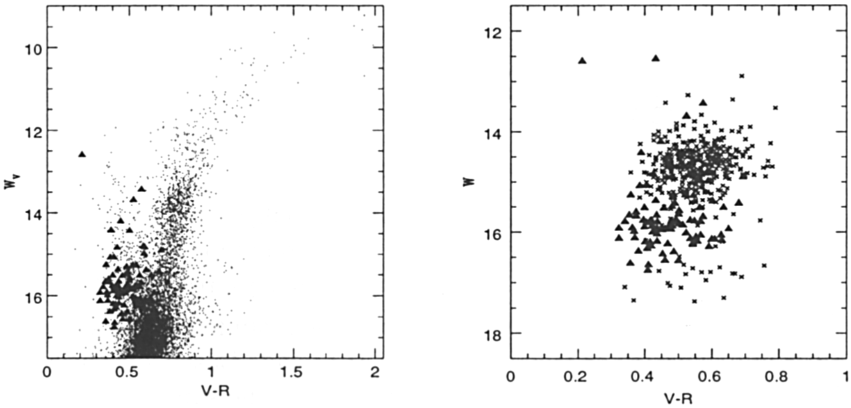

Fig. 3 - Color-magnitude diagrams of bulge δ Scuti stars, compared with Baade's window stars (left panel), and bulge RR Lyrae stars (right panel).

Are the bulge δ Scu stars also blue stragglers? In order to answer this question, Figure 3a shows the MACHO W_V *vs* $V - R$ color-magnitude diagram of Baade's window (only 5000 stars are plotted). This color-magnitude diagram shows a prominent red giant branch (RGB), a red horizontal branch (or RGB clump) at $W_V = 13.5 - 14$, and the blue disk main sequence with $V - R < 0.5$. The bulge turn-off would be located at the faint limit of our photometry in this field. Note, however, that we reach the bulge turn-off in other MACHO fields which are less crowded than Baade's window. The δ Scu stars with $0.08^d < P < 0.20^d$ from all the bulge fields are also plotted (filled triangles) in Figure 3a. From this Figure we conclude that their colors and reddening-independent magnitudes are consistent with bulge blue stragglers. This is confirmed also by the location of δ Scuti stars (triangles) with respect to bulge RR Lyrae type ab (crosses, from Alcock et al. 1997) in the color magnitude diagram shown in Figure 3b.

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4. The Distribution along the Line-of-sight

Figure 4a shows the W_V magnitude distribution of δ Scu and RR Lyr stars. The δ Scu distribution is very peaked, with $FWHM = 0.6 \pm 0.05$ mag. This argues for δ Scu stars pulsating in a single dominant mode. The observed magnitude scatter is consistent with the line-of-sight depth of the Galactic bulge, and it would be larger if pulsators in two or more different modes are represented. Also note that the observed FWHM is slightly smaller than that of RR Lyrae type ab stars. This means that the metallicity dependence of the magnitude $\Delta M_V / \Delta[Fe/H]$ is smaller, either because the RR Lyrae have a wider metallicity distribution, or because their spatial distribution is slightly different.

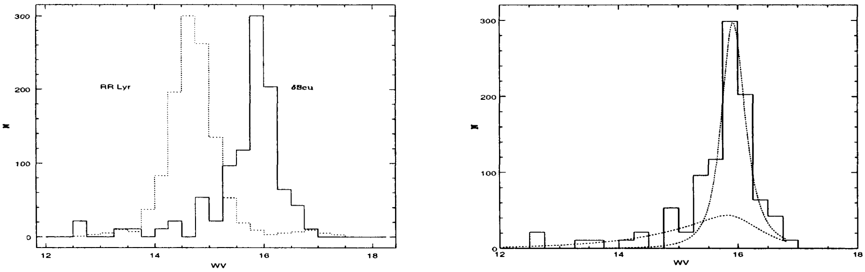

Fig. 4 - Luminosity distribution of δ Scu stars (arbitrary normalization).

We assume that the line of sight distributions of δ Scu and RR Lyrae stars are similar. In the sky, these stars are concentrated towards the inner fields, as expected if they follow the bulge radial density profile rather than the disk, which would show a more uniform, shallower distribution.

In order to decide if the stars in the present sample belong to the disk or the bulge, one can assume that all δ Scu stars have roughly the same magnitude, and compute the expected magnitude distribution for these two Galactic components integrated along the line of sight. Figure 4b shows the observed magnitude distribution, along with the line of sight density distribution expected for the bulge and the disk (upper and lower dotted curves, respectively). The disk is assumed to be a double exponential of the form $\rho_d \propto exp(-r/h_r)exp(-z/h_z)$, with scale-height $h_z = 0.3$ kpc, and scale-length $h_r = 3$ kpc, and the bulge is assumed to be approximated by a power law of the form $\rho_b \propto r^{-n}$, with $n = 3.5$. The counts have been normalized arbitrarily. If all the δ Scu stars from Table 1 were disk stars, the FWHM of their observed magnitude distribution would be ~ 2 mag, as seen in Figure 4b. We conclude that the majority of the stars in our sample are bulge δ Scu stars. However, about 10% of the δ Scu stars shown in Figure 4 are significantly brighter than the mean. These could be δ Scu stars in the foreground disk, or merely blends.

5. Conclusions

We have analyzed a sample of δ Scu variable stars within a narrow period range, $0.08^d < P < 0.20^d$, identified in the MACHO bulge database. The colors and magnitudes of these stars are consistent with them being bulge blue stragglers. A comparison of the observed light curves with the recent theoretical models of Bono et al. (1997) suggests that the present sample consists mainly of second overtone pulsators.

We note that adopting the P–L–Z relations of Fernie (1992), McNamara (1995), or Nemec et al. (1995), different mean absolute magnitudes can be obtained. Distances measured using these δ *Scu* stars are presently very uncertain, because of the unknown metallicity dependence and pulsational stages. The determination of an improved P–L relation for δ Scu stars, both from the theoretical and observational sides, would be very useful. For example, based on the tightness of the magnitude distribution of the bulge δ Scu stars, when a firm P–L relation is established, they could yield an independent distance to the Galactic center as accurate as that measured using RR Lyrae stars.

We would then like to stress the need for more a more complete exploration of the parameter space (models with different masses, temperatures and luminosities). Spectroscopy of the present sample is also needed in order to determine the abundances and masses of these stars, and to decide if δ Scu stars are the mere metal-rich extension of SX Phe stars.

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References

Alcock, C., et al. (The MACHO Collaboration) 1997, ApJ, 474, 217
Bono, G., Caputo, F., et al. 1997, A&A in press (astro-ph/9609087)
Breger, M. 1995, Baltic Ast., 4, 423
Cook, K. H., et al (The MACHO Collaboration) 1995, ASP No. 83, p. 221
Fernie, J. D. 1992, AJ, 103, 1647
McNamara, D. H. 1995, AJ, 109, 1571
Nemec, J. M., Mateo, M., Burke, M., & Olszewski, E. 1995, AJ, 110, 1186
Nemec, J. M., Nemec, A. F. L., & Lutz, T. E. 1994, AJ, 108, 222
Rodriguez, E., Lopez de Coca, P., Rolland, A., et al. 1994, A&AS, 106, 21