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RR Lyrae Stars in Globular Clusters

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Abstract. Of the several types of variable stars that occur in globular clusters, RR Lyrae stars have deservedly received the most attention. These stars are ideally suited for comparisons between evolution and pulsation theory, they play a prominent role in distance determinations, and are valuable tracers of the oldest stellar populations. After a brief discussion of technical aspects, we review some of the recent observational work.

1. Introduction

The study of variable stars in Globular clusters (GCs) is of obvious importance due to: (i) GCs are simple stellar populations with no obvious self-enrichment except in the cases of ω Cen and M22; (ii) the stellar contents are all at the same distance; (iii) the GCs are all of similar age to the Galaxy, facilitating comparisons; (iv) several types of variables stars occur in GCs – Population II Cepheids, RR Lyrae stars, SX Phe stars, cataclysmic variables – allowing in particular luminosity comparisons (Nemec, Nemec, & Lutz 1994). However, there are difficulties as well: (i) GCs are high density environments, where interactions and mass segregation can occur; (ii) they are only approximately as old as the Galaxy, the range of ages, apart from a few clusters, may be rather small (VandenBerg 1999) and correlated with metallicity, but age ranges of 3-5 Gyr have been suggested by others; (iii) some clusters may have been accreted by our Galaxy; (iv) relevant for RR Lyrae stars, horizontal branch (HB) morphology is a function of at least two parameters, and the relative importance and/or necessity for further parameters is a matter of debate.

2. Technical Advances

Larger detectors are becoming more common, with monolithic scientific CCDs reaching 2K×2K and 2K×4K pixels, commercially available from both SITe and EEV. The 2K×4K devices are specifically designed to be buttable on three sides, and several groups are building mosaics using these CCDs as building blocks. Both ESO and NOAO have 8K×8K mosaics in regular use, and CFHT has a 8K×12K. IR arrays have reached 1K×1K in both InSb and HgCdTe; 2K×K are expected within a year, with mosaic imagers using several devices being planned. Mosaic instruments are very expensive, and, in general, are overkill for study of galactic GCs, where for all except the largest clusters a ~15 arcmin field is adequate. Variable star work in clusters makes more demand on image quality rather than on ultimate field size, particularly for study of variables in the crowded cluster cores. Telescopes in general are now designed not to degrade the natural site seeing, with spectacular early results from new large facilities such as Gemini, Subaru, and VLT. The use of adaptive optics systems is still in its infancy, with the ability to do high-accuracy photometry in crowded regions still to be demonstrated. HST has been used extensively to study GCs, including the unexpected discovery of multiple HB clumps in NGC 2808 (Sosin et al. 1997) and studies of the nature of blue stragglers (e.g. Piotto et al. 1999). However, the use of this facility for variable star work has been minimal, apart from the well-publicized work on Cepheids in nearby galaxies to determine the Hubble constant.

Turning now to data-reduction techniques, most studies in recent years have used the programs DAOPHOT (Stetson 1987, 1995) or DoPhot (Schechter, Mateo, & Saha 1993). These programs have evolved over the years, with more sophisticated PSFs and fitting techniques. The latest variant of DAOPHOT, called ALLFRAME, provides improved photometry for the case where there are multiple frames of the same field by using all available information to establish the star list, and, together with robust techniques for identifying variables using observations in two or more colors (Welch & Stetson 1993), has been very successful for variable star work. A new reduction program (ISIS) is described by Alard (2000). It appears to provide substantial gains in photometric accuracy when applied to measuring variable stars in crowded fields.

3. Fourier Decomposition

Fourier decomposition of variable star light curves, and the characterization of the resulting Fourier parameters in terms of physical quantities, is a technique pioneered by Simon (1988) and more recently extended by Simon & Clement (1993), and by Kovács and co-workers (Kovács & Jurcsik 1996, 1997; Jurcsik & Kovács 1996; Kovács & Kanbur 1998). A recent application of these methods is the study by Clement & Shelton (1999a) who compare the properties of the RR Lyrae stars in M9 with those in M3, M68, and M107. This is a powerful test, since these four clusters cover a very wide range of metallicity, from [Fe/H] $= -0.99$ for M107 to [Fe/H] $= -2.09$ for M68, on the Zinn (1985) scale. They find cluster-cluster separation in both the Fourier parameters ϕ_{31} and ϕ_{41}, but note that the Jurcsik & Kovács (1996) relationships between these Fourier parameters, period, and [Fe/H] do not seem to fit the data very well. Various [Fe/H] and M_V relations are found to lack consistency, and they conclude that further progress will require data for RR Lyrae stars in additional clusters. Such an analysis is underway, with a preliminary report in Walker & Kovács (2000).

An interesting complementary method, that appears to function well on more sparse and/or lower accuracy data than possible for Fourier analysis, is that of principal components analysis (PCA), described by Kanbur et al. (2000). Their initial application was for Cepheids, but the method, suitably calibrated, should be equally appropriate for RR Lyrae stars.

4. [Fe/H] via Caby Photometry

The determination of [Fe/H] for RR Lyrae stars traditionally involves use of the ΔS method (Preston 1959) which requires spectroscopic measurement of Ca II H & K and Hydrogen line equivalent widths, measured near minimum light. The assumption that [Ca/Fe] is near constant for [Fe/H]$\lesssim -0.6$ seems reasonable (Carney 1996, Stetson et al. 1999), so metallicities obtained by this method should be able to be compared with (say) [Fe/H] for red giant branch stars. A major disadvantage of the ΔS method is that it requires knowledge of the light curve phase. In addition, the calibration for RRc stars appears poorly established and is probably inconsistent with that for RRab stars. A photometric method for determining [Ca/H] abundances in stars of spectral types A or later has been developed by Anthony-Twarog et al. (1991) and extended to RR Lyrae stars by Baird (1996) and Baird & Anthony-Twarog (1999). It combines measurement of the Ca II H & K lines with a filter of width 100 Å with Strömgren b and y, defining the hk index as $hk = (\mathrm{Ca} - b) - (b - y)$. Baird (1996) found that the hk index retains good sensitivity even for the hottest RRc stars, and demonstrated that isometallicity lines formed in the $hk/(b-y)$ diagram are single-valued with respect to both $b-y$ and hk. Thus the $hk/b-y$ diagram can be used to give RR Lyrae metallicities throughout the pulsation cycle, including the rising branch where ΔS results are incorrect. Further work is needed to firm up the RRc calibration, but for RRab stars an accuracy of 0.1 – 0.2 dex in [Ca/H] per measurement is possible (Rey et al. 1999).

5. Are RR Lyraes in OoII Clusters Evolved?

The precise evolutionary status of GC RR Lyrae stars is clearly intimately involved with the general problem of HB evolution. It has long been recognized (Arp 1955) that the dominant driver of HB morphology is metallicity; the clear need for one or more extra parameters has for many years been a hotly debated topic (the second parameter problem) with age, helium abundance, rotation, and mass loss being some of the possible candidates. The non-monotonic relationship between HB morphology and metallicity, whereby clusters with $-2.0 <$ [Fe/H] < -1.7 have blue HBs and few RR Lyrae stars, has been advocated as at least a partial explanation for the Oosterhoff (1939) dichotomy. In both clusters and field (Suntzeff, Kinman, & Kraft 1991) RR Lyraes fall into either a short- and a long-period group, with an apparent correlation with metallicity in the sense that the longer period group has lower metallicity. Explaining this behavior has proven to be a non-trivial problem, as is well-summarized in Smith's (1995) monograph. The period–amplitude (P–A) relation for RRab stars also appears to separate stars by metallicity, as shown originally by Preston (1959) and studied in detail for six GCs by Sandage (1981). He used the P–A relation for M3 as a fiducial and determined $\Delta \log P$ for each cluster relative to this relation, showing that there was a strong correlation between this quantity and metallicity. A consequence of this result is a steep relation between mean $\langle V \rangle$ magnitude for RR Lyrae stars and [Fe/H], which implies relatively bright metal-poor RR Lyrae stars. This is turn affects ages of GCs and the RR Lyrae distance scale calibration (Walker 1992).

The importance of the details of post-ZAHB evolution for RR Lyrae stars in clusters with a blue HB morphology was first argued by Gratton, Tornambé, & Ortolani (1986), and then by Lee, Demarque, & Zinn (1990) and Lee (1991) on the basis of Lee's HB evolutionary calculations. He showed that a monotonic distribution of ZAMS stars with temperature could result in a non-monotonic distribution of a given population due to details of the routes of the evolutionary tracks, and in particular stressed that RR Lyrae stars in clusters with predominantly blue HB structure were stars making the final journey across the instability strip from blue to red, at a luminosity significantly higher than that for stars originating from a ZAMS position in or close to the instability strip.

Recent work has allowed significant progress in understanding the relative importance of the evolutionary effect. Clement & Shelton (1999b) and Clement (2000) find by examining light curves for RRab stars in several clusters, after discarding any stars displaying the Blazkho effect, that the V amplitude at given period is a function of Oosterhoff type alone, and not of metallicity. The few bright RRab stars in Oosterhoff I clusters (such as M3) precisely fit the Oosterhoff II $P-A$ relation. This supports the conjecture that the RR Lyrae stars in Oosterhoff type I clusters lie near the ZAHB, while those in Oosterhoff type II clusters (and the few bright RR Lyraes in OoI clusters) are evolved, and more luminous, stars that originate from a ZAHB position hotter than the instability strip.

An identical conclusion is reached by Lee & Carney (1999) who analyze the CMDs and RR Lyrae properties for the second-parameter pair M2 and M3. The clusters have [Fe/H] $= -1.62$ and -1.65 respectively, but very different HB morphologies, $(\mathrm{B-R})/(\mathrm{B+V+R}) = 0.92$ for M3 and 0.08 for M2, where B, V, R are the numbers of blue HB stars, RR Lyrae stars, and red HB stars, respectively. Both main sequence fitting and a period-shift analysis lead to the conclusion that the RRab variables in M2 are in the mean 0.2 mag brighter than those in M3; from these results and comparisons with other clusters they conclude that the evolutionary effect is responsible for the magnitude difference, and that this result is supported by a comparison between the mean rates of period change for the M2 and M3 variables. They further find an age difference of 2 Gyr between the clusters, supporting age as being the global second parameter. Note that Vandenberg (1999) does not espouse this interpretation, although Lee et al. (1999a) present new HB model calculations showing that HB morphology is much more ($\sim$40 percent) sensitive to age than previously thought. Therefore, an interpretation where age is the global second parameter and local effects, such as enhanced mass loss in high density clusters, are responsible for peculiar HB morphology (e.g. extended blue tails, multi-modal distributions), seems viable.

Another piece of evidence comes from a new study of the RR Lyrae stars in NGC 6388 and 6441 by Pritzl et al. (2000; see also Layden et al. 1999). Despite these clusters having [Fe/H] ~ -0.5, they have blue HB structure and sloping HBs that can be interpreted in a variety of ways (Sweigart & Catelan 1998). Note that sloping HBs in slightly more metal poor clusters such as NGC 6362, [Fe/H] $= -1.1$, and NGC 1851, [Fe/H] $= -1.3$, can be explained by canonical HB models (Brocato et al. 1999). The RR Lyrae period distribution and behavior in the $P-A$ diagram match those for RR Lyrae stars in very metal poor clusters such as M15 or M68, although they are perhaps even more extreme. Thus these clusters could well be classified as Oosterhoff II, and are the most extreme examples disproving the correlation between metal abundance and Oosterhoff type.

6. ω Cen

The GC ω Cen, apart from being the most massive GC in our Galaxy, contains stars with a wide range of metal abundance. Since it has a well-populated HB and some ~180 RR Lyrae stars, it should allow definitive tests of magnitude–metallicity relations, etc. However, early photometry and ΔS abundances show no strong correlations, together with a surprisingly wide metallicity range (Dickens 1989). New results (Lee at al. 1999b, Rey et al. 1999) do much to resolve these issues. The metallicity distribution for the RR Lyrae stars now matches that for the RGB. Bright, highly evolved stars with $-1.9 <$[Fe/H]< -1.5 are identified via the $P-A$ diagram, in agreement with predictions from HB models. In particular, the M_V(RR) - [Fe/H] relation from the new data are consistent with Lee's (1991) models, which predict a near step-function change in luminosity at [Fe/H] $= -1.5$. If the stars in the abundance range $-1.9 <$[Fe/H]< -1.5 are excluded, then the slope of the magnitude–metallicity relation is found to be ΔM_V(RR)/Δ[Fe/H]$= 0.24 \pm 0.04$, i.e. a "normal" slope for the magnitude–metallicity relation is derived when the evolved stars are excluded.

7. Summary

I have summarized some of the observational work on RR Lyrae stars carried out in the recent past; theoretical work done during this time is certainly no less exciting or important, and some is presented in other papers at this meeting. Work remains. High-quality CMDs are lacking for many clusters, as are their detailed abundances; the new 8-m telescopes in the south will redress at least the latter. RR Lyrae stars in many GCs lack modern observations, so there is still careful variable star photometry waiting to be done, while revisiting existing work using new techniques (Alard 1999) and improved reddenings (Schlegel, Finkbeiner, & Davis 1998) would be of value. Many of the less studied clusters are those with high foreground reddening and significant field star contamination; here photometry in the IR has an advantage and array sizes are now sufficient to allow such a task to be carried out efficiently.

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Discussion

Giuseppe Bono: Did you check whether the RGB clump you found on the RGB of ω Cen can be explained as the canonical RGB bump?

Alistair Walker: Yes, the clump corresponding to the metal-rich component does not lie on the RGB of the metal-poor components.

Mario Mateo: We tried to look for a possible stream associated with ω Cen using the CTIO 4-m last May. To an approximate limit of $\Sigma_V \approx 29 - 30$ mag/arcsec^2 we found nothing. Weather interfered a bit, and a more complete grid should be carried out, but for now, no dwarf.

Alistair Walker: This is an interesting result, although it is not clear how much of an extended component would remain after (say) 10 Gyr.

Giuseppe Bono: Did you check whether the young Red Clump stars fall close to the RGB clump?

Alistair Walker: Yes. The young red clump appears to be sufficiently displaced in color from the older RGBs to avoid confusion.

Don Kurtz: How does a merger with a dwarf galaxy help understand the metal-rich giant branch in ω Cen better than a merger with a galactic globular cluster?

Alistair Walker: Multiple star formation bursts are qualitatively more indicative of a dwarf galaxy (nucleated in this case) rather than a globular cluster, but this observation is certainly not proof.