THE GLOBULAR CLUSTER ω CENTAURI AND ITS RR LYRAE VARIABLES

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Abstract. The significance of some of the unusual characteristics of the globular cluster ωCentauri in various fundamental problems is explored. Interest is centred on the properties of the cluster RR Lyraes, and what they can contribute to studies of early cluster chemical enrichment, stellar pulsation, the distance scale, stellar evolution, stellar ages and the Oosterhoff period-shift problem. This article, which is intended to highlight problems and progress rather than give a comprehensive review, includes new results based on photometry of the RR Lyraes, red giants, subgiants, horizontal-branch and main sequence stars in the cluster.

1 INTRODUCTION

1.1 The cluster

The globular cluster ωCentauri has been the subject of intensive study over the last two decades. The motivation for much of this work has been the realisation that the cluster possesses unusual properties, first hinted at in its peculiar HR diagram (Woolley 1966) which showed a large intrinsic scatter in the red giant branch. One of the more notable of its peculiarities is the spread in chemical composition, either measured or inferred among all samples of stars studied (red giants, subgiants, RR Lyraes and main-sequence stars).

ωCen is also the most luminous and massive of the galactic globular clusters, properties which might well be related to its apparent peculiarity. This fact leads one immediately to the first major question posed by the cluster's properties, is the cluster unique in some fundamental way or is it just an extreme example of a galactic globular cluster, its "peculiarities" showing up primarily because of the richness of the stellar sample it provides? However, because the cluster is so massive, this in itself might be responsible in a fundamental way (e.g. in the conditions at formation) for the cluster's apparent uniqueness. This question assumes great importance if we are to apply what we learn about the physical causes of the properties of the "sub-populations" in ωCen to interpret the properties of other clusters.

In many ways, ωCen resembles a small galaxy. It is noticeably elliptical in shape, as expected from its observed rotation about the minor axis (Harding 1966). The existence of identifiably different stellar populations within it provides a perhaps unique opportunity to study differential effects between them, especially valuable in view of

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the close proximity of the cluster as compared to any galaxy, even the nearby dwarf spheroidal systems which its stellar content appears to resemble.

1.2 The RR Lyrae variables

Since the turn of the century, the RR Lyrae variable stars in ω Cen have attracted the attention of astronomers. Pioneering work by Bailey (1902) was followed later by a major study of Martin (1938), a classic paper which has become the fundamental reference work for subsequent studies. More recent papers include a study of the period changes (Belserene 1964), a photometric study (Dickens & Saunders 1965) and spectroscopic studies by Freeman & Rogers (FR, 1975), Butler Dickens & Epps (BDE, 1978) and Gratton, Tornambé & Ortolani (GTO, 1986).

These spectroscopic studies confirmed that the range in chemical composition expected from the intrinsic spread in colour on the giant branch occurred also among the RR Lyrae population. The spread in abundance is now firmly established from spectroscopic studies of individual giant stars (e.g. Cohen 1981; Caldwell & Dickens 1988), and has demonstrated that both light and heavy elements are involved, the spread arising most probably from both primordial and mixing origins (see Smith 1987 for a comprehensive review).

To set the scene for what follows, Figure 1 shows a composite colour-magnitude diagram (CMD) for ω Cen, in which stars brighter than about V = 16 are taken from Dickens et al. (1988) and those fainter from Noble (1987). Note the huge colour spread amongst the giants, and the more modest spread on the main sequence, both being much larger than can be accounted for if all the stars had the same heavy-element abundance.

2 CLUSTER FORMATION AND EARLY CHEMICAL ENRICHMENT

Evidence bearing on conditions at the time the cluster was formed comes from the observed range in heavy-element abundance, its shape and the existence or otherwise of a radial gradient. We look first at the RR Lyraes, which provide the only **direct** evidence of the full range and shape of the abundance distribution.

Figure 2 shows a histogram of the distribution with [Fe/H] for all RR Lyraes for which [Ca/H] has been determined by the ΔS method. Most values come from BDE, which incorporated FR, but stars in common with GTO have new values obtained from averaging with theirs. The filled part of the histogram represents the Bailey c-type variables. The overall distribution is clearly asymmetric, tailing off slowly towards the more metal-rich end. The c-types alone show a similar distribution, but there is a deficiency of metal-rich stars of this type. The ab-types alone show less marked asymmetry. Although there may appear to be no immediately obvious reason to separate the sample according to type, and therefore pulsation mode (ab being fundamental and c first harmonic), the stars do occur in different parts of the horizontal branch (HB), and this would be influenced in part by their abundance,

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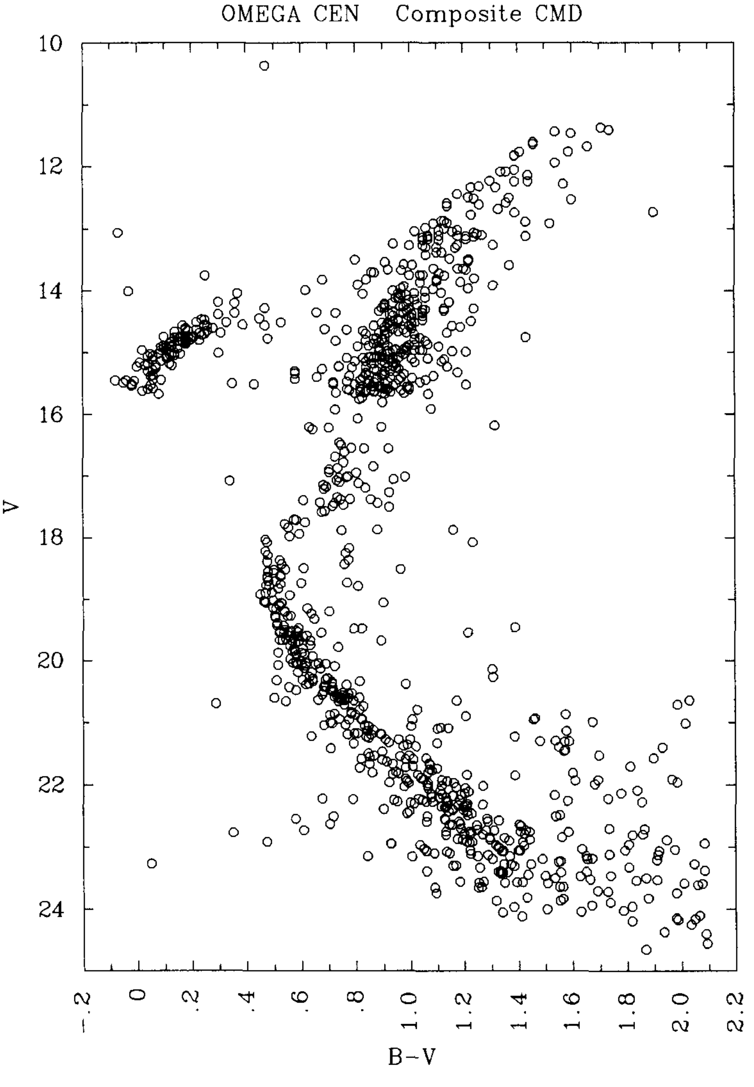
Figure 1. A composite CMD for ω Cen, in which stars brighter than V=16 comprise photographic photometry from an annular region, and those fainter from CCD photometry of several fields located about 20 arcmin west of the cluster centre.



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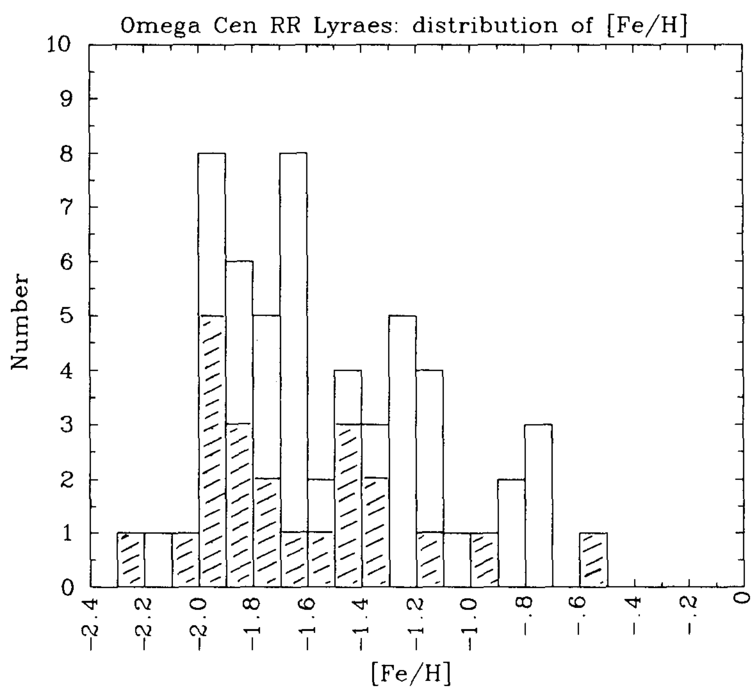
especially if they lay near the zero-age HB (ZAHB). On the basis of HB models, one might expect a tendency for the (bluer) c-types to be on average more metal-deficient, as is indeed suggested by their distributions. Another interesting property of these distributions is the fairly strong indication of bimodality. Although difficult to prove conclusively, we have investigated this possibility further, and show in Figure 3 a Maximum Likelihood fit of a double-Gaussian distribution to the full sample (the binning is slightly different in this diagram). The parameters derived for the two underlying populations are listed in Table 1. From Monte-Carlo simulations, we find that the probability (in a Kolmogorov-Smirnov test) that this double-Gaussian is a true representation of the data is only about 5%, i.e. on the borderline of being a satisfactory fit.

Thus we are teased with the possibility that there could be two underlying populations of stars in ωCen, as sampled in the instability strip, which might have arisen in two discrete bursts of star formation, or even in a merger of two separate systems (Searle 1977). However we

Figure 2. The distribution of [Fe/H] amongst the ωCen RR Lyraes, as derived from [Ca/H] measurements. The filled part of the histogram represents the c-type variables alone. The distribution is clearly asymmetrical and also looks bimodal.



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are not yet able to rule out a more steady enrichment process in which an initial burst of star formation forming the metal-poor peak was followed by a gradual decline in the rate as the interstellar material became steadily enriched.

Turning now to the question of a radial gradient in calcium abundance, as has been claimed by Freeman (1985) and earlier discussed by Smith (1981), we show in Figure 4 abundance histograms for three radial groupings. These show marginal evidence for a bias towards more metal-poor stars at radii greater than 10 arcmin. This effect is perhaps more marked in the c-types, as shown in Figure 5 where there appears to be a deficiency in metal-richer c-types at the larger radii

Table 1.
Parameters for underlying populations

Sample	No.	<[Fe/H]>	dispersion
metal-poor	26	-1.84	+/-0.17
metal-rich	30	-1.26	+/-0.35

Figure 3. The Maximum Likelihood fit of a double-Gaussian to the RR Lyrae abundance distribution.

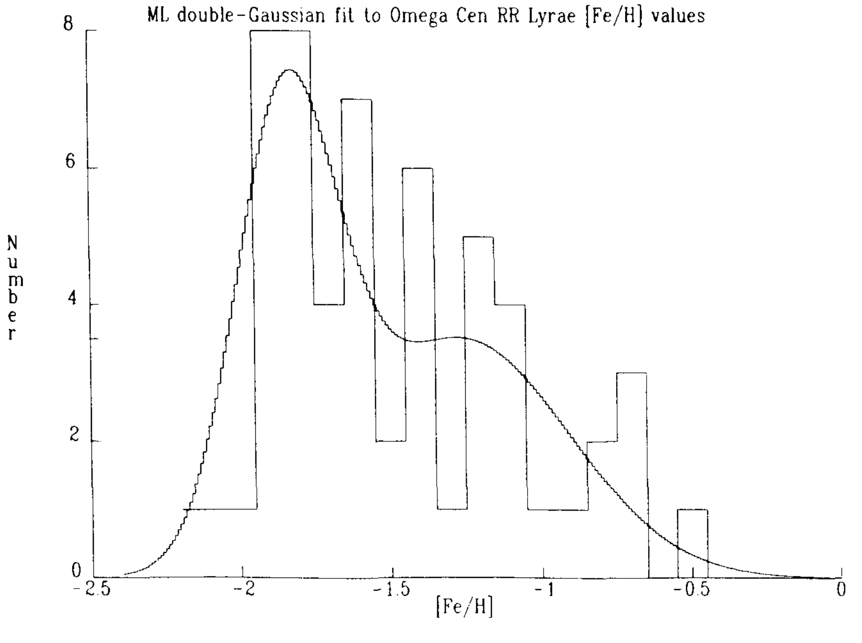

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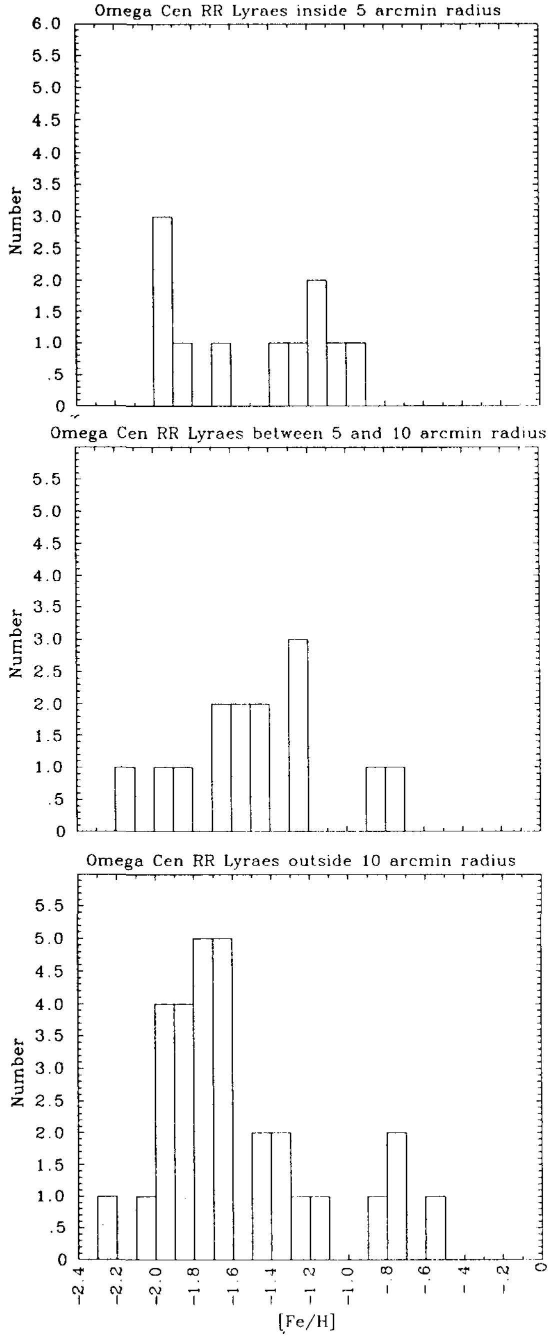
Figure 4. RR Lyrae abundance distributions for three radial groupings. The outer group show a less uniform distribution, with an excess of metal-poor RR Lyraes as compared to the inner groups.



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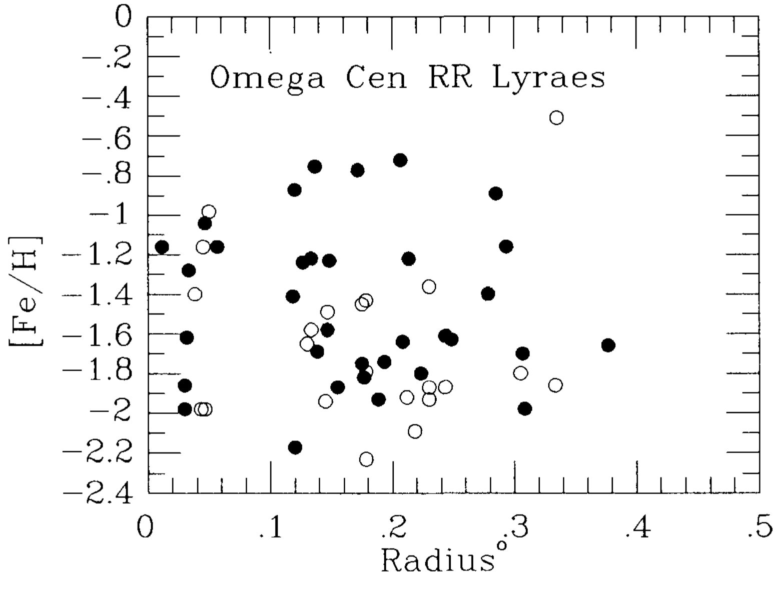
in contrast to the ab-types. None of these trends appear to have formal statistical significance, but it must be kept in mind that even moderately strong gradients would be obscured in projection. A substantially larger sample of stars with abundance measurements would clearly be of interest in order to follow up these tantalising trends, which are similar in kind to those found in galaxies, and if real, must have been laid down at the epoch of star formation in the cluster.

Indirect evidence on the abundance distribution comes from stellar colours in various parts of the CMD, on the assumption that the intrinsic width (corrected for observational error) is largely due to a variation in abundance. This is indeed the most likely explanation for giants, subgiants and main sequence stars; in the turnoff region, a range in age would also contribute to the spread. Figure 6 shows a distribution with colour for a half-magnitude slice of the giant branch, between radii of 10 and 25 arcmin, taken from the data of Dickens et al. (1988). This is a typical distribution for stars on the giant branch, with a suggestion of a red (higher metal content) tail as found in the RR Lyraes. A similar (asymmetrical) distribution in residual (V-K) colour (an abundance parameter) was obtained for all stars studied

Figure 5. [Fe/H] versus radius for RR Lyraes in ωCen; open circles are c-types, filled circles ab-types. The most metal-rich variable is V84, formerly designated an ab-type but now thought to be an overtone pulsator, and hence a c-type. In spite of this, there appears to be a deficiency of metal-rich c-types outside a radius of 0.1 degree.



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by Persson et al. (1980, Figure 4). Their photometrically unbiased sample showed no asymmetry, but the large spread in colour, and hence abundance, remained.

An intrinsic spread in abundance is also implied for subgiants, on the basis of the distribution with colour found by Da Costa & Villumsen (1981, Figure 2). The observations again show a red (presumed high abundance) tail, but no detailed analysis of these data appears to have been published.

Observations of lower subgiant and main-sequence stars are illustrated in Figure 7, taken from Noble (1987). Superposed on the data are 16 Gyr isochrones for four values of [Fe/H]. Since the photometric accuracy on the upper main sequence is of order 0.01 to 0.02 magnitude, it is clear that a large range in [Fe/H] amongst the stars can account for the observed range in colour, the extreme isochrones of [Fe/H] = -2.23 and -0.77 roughly delineating the extremes. Although there is some contamination by field stars, this does not materially affect this conclusion, which therefore suggests a "primordial" spread comparable to that shown by the RR Lyraes. These results are further quantified in

Figure 6. Distribution with colour in a sample of red giants in ω Cen. The blue side of the distribution is contaminated with AGB stars. Allowing for this reinforces the apparent asymmetry, which has a red, presumed more metal-rich tail.

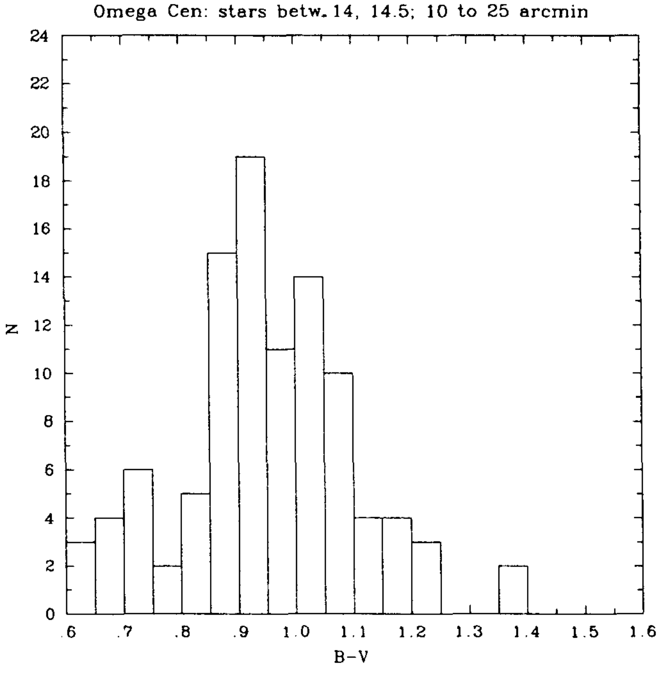

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Figure 8, which shows histograms of the observed colour residuals about a fiducial line close to the isochrone for [Fe/H] = -1.27 in Figure 8, for one magnitude slices. The simple Gaussian fits to the residuals shown are not good representations in general, and the true shape of these distributions is yet to be investigated. Note that the isochrones indicate a non-linear relationship between colour and metallicity on the main sequence and subgiant branches. These results will be fully discussed elsewhere (Noble et al. 1989).

In summary, all evidence points to a large intrinsic spread in [Fe/H], from less than or of order -2.0 to about -0.5. Evolved stars indicate a skew distribution having a high metal-abundance tail. There could be at least two underlying distributions. Further work, some already in hand, promises to sharpen these results considerably.

Figure 7. CMD of the main sequence and turnoff region of ωCen. Four isochrones of differing [Fe/H] are shown, the extreme ones embracing virtually all stars on the upper main sequence and subgiant branch.

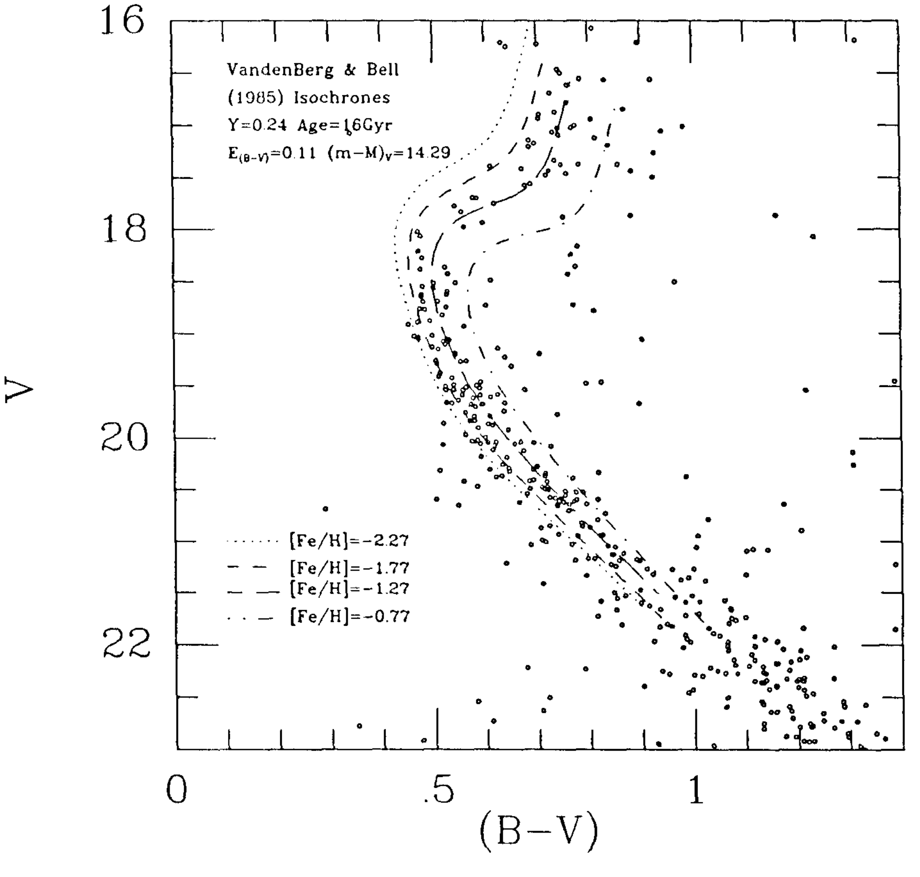

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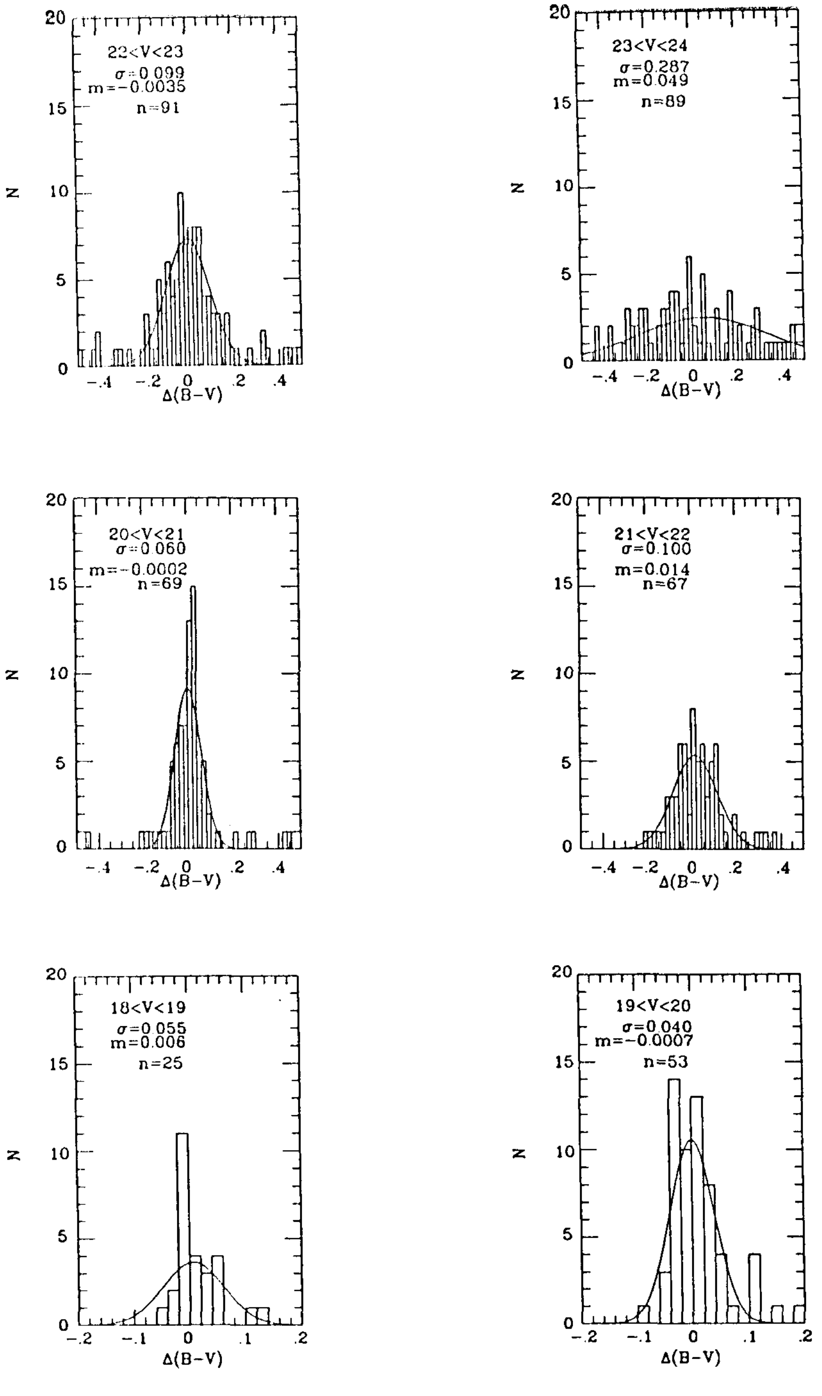
Figure 8. Histograms of colour residuals measured from a fiducial mean main-sequence line, for one magnitude slices. Fitted Gaussians are shown, with indicated dispersions much larger than the observational errors.



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3 STELLAR PULSATION

The pulsational properties of the RR Lyraes of course play a central role in our understanding of the stars themselves, but also in understanding the peculiarities of ωCen, and in most of the wider questions being addressed here. Accurate light curves in several wavebands enable comparisons with sophisticated modelling, and provide the data necessary to derive important physical parameters that can be used to test stellar evolution theory (including some assessment of the correctness of the input physics to models; e.g. see Sweigart et al. 1987). The data to be discussed for ωCen are primarily B,V photometry by Dickens & Bingham (1989), but some reference will be made to Walraven photometry by de Bruijn & Lub (1987) and infrared K photometry by Longmore et al. (1989).

The position of the RR Lyraes in the CMD is shown in Figure 9. An equilibrium colour, $(B-V)_{eq} = 2/3 \langle B-V\rangle_{mag} + 1/3\ (\langle B\rangle_{int} - \langle V\rangle_{int})$, has been calculated following Lub (1977), which is seen to combine both

Figure 9. The positions in the CMD of all the RR Lyraes with B,V photometry are given. The location of the blue edge of the instability strip (HBE) is shown as a vertical line. In this and subsequent Figures, open circles are c-types, filled circles ab-types. Most stars occupy a well-defined region about 0.1 magnitude deep, with only a few stars (flagged) lying off. It is believed that the fainter stars lie near the ZAHB, whereas the bulk are more evolved (see text).

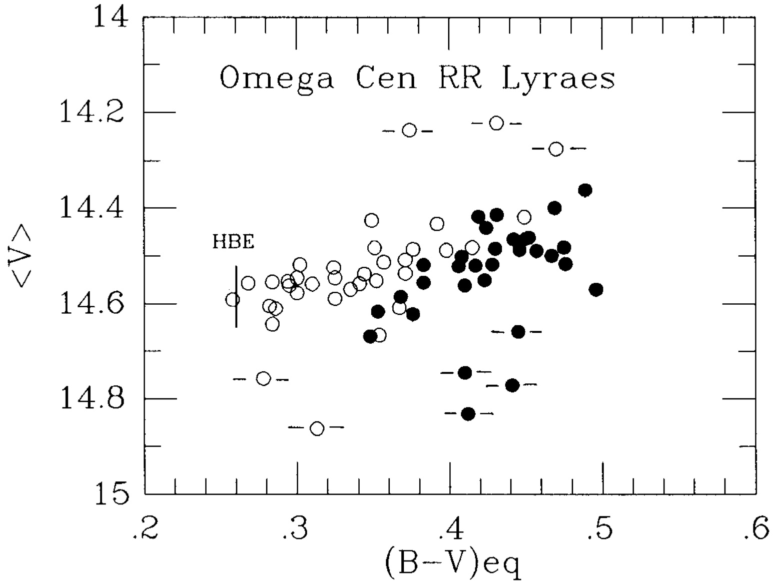

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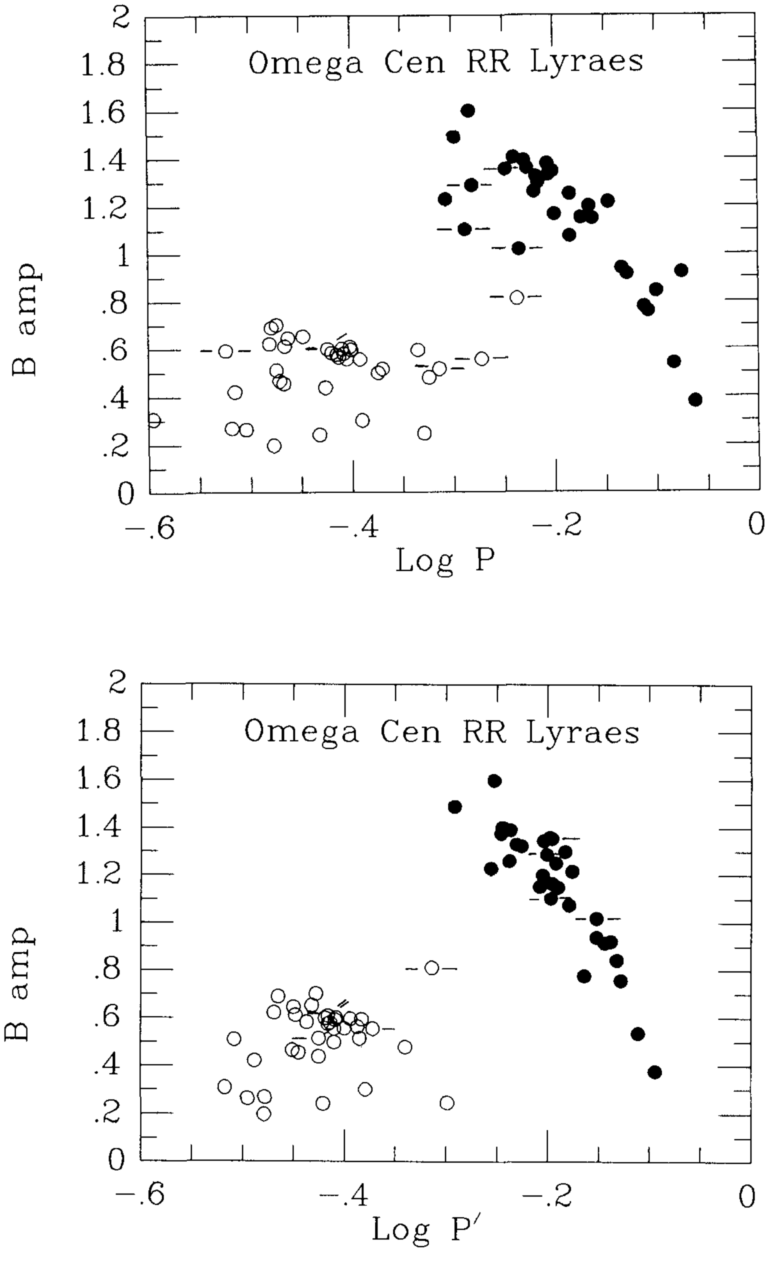
Figure 10. The correlation of blue amplitude with a) log P and b) log P′ = log P + 0.33 (m_{bol} - <m_{bol} >) where <m_{bol} > is the mean value at the observed colour, and P′ the "corrected" period. The smaller scatter in b) shows that some of the luminosity spread is real.



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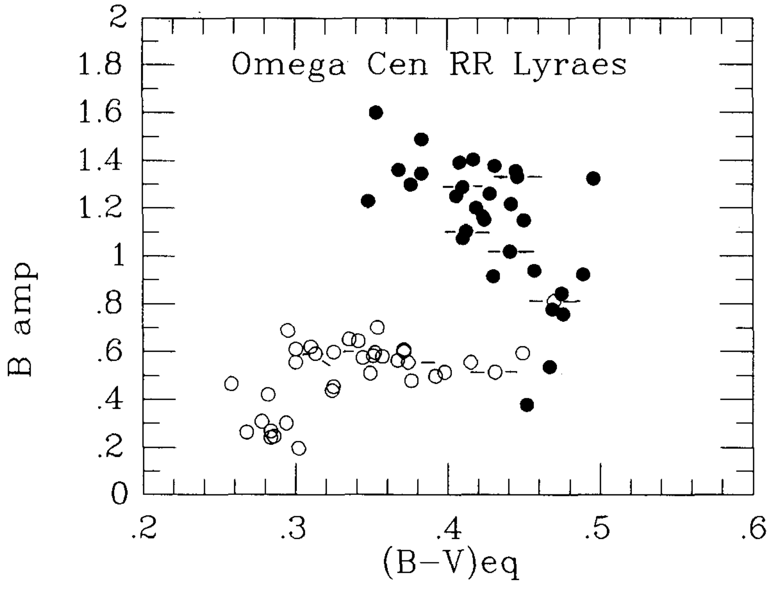
magnitude and intensity means. Although most variables occupy a well-defined region on the HB, as in other clusters, about 10% of the sample lie well away from the HB, and are flagged in this and the subsequent three figures. Only one of these stars is a non-cluster member. These stars tend to lie off other correlations between the light-curve parameters, and must differ in some important property from the majority of HB stars (see, for instance the period-amplitude diagram of Figure 10(a)). The individual periods may be corrected for the differing luminosity within the cluster, by normalising to the mean relationship followed by the stars in Figure 9. This is convenient when comparing mean properties between clusters, as for example in the (corrected) period-amplitude diagram shown in Figure 10(b). The location of the mean line of the ab-types in this diagram has often been used to define the Oosterhoff period-shift between clusters. The tightening of the period-amplitude relation is evidence that some of the luminosity spread is indeed real, as shown by van Albada & Baker (1973).

Figure 11 shows how the amplitude varies across the instability strip. Note the occurrence of a number of small-amplitude c-types close to the

Figure 11. The correlation of blue amplitude with equilibrium colour for the complete B,V sample. Note the occurrence of a number of very small-amplitude c-types near the blue edge. These stars appear to be absent in M15 (see Bingham et al. 1984), whereas it is the multimode variables occurring at the transition colour in M15 that are entirely absent in ω Cen. These properties are thought to be related to the track morphology (see text).



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blue edge; these stars do not appear to exist in M15 (Bingham et al. 1984, Figure 16). This could be a selection effect, but might also relate to differences in track morphology between the clusters. Another notable difference between these two clusters is the presence of many multimode variables in M15, right at the transition temperature, and the complete absence of any such stars in ωCen (Stellingwerf & Dickens 1983, Nemec et al. 1986). Again this could be related to the details of track morphology, as has been discussed by Bingham et al. (1984) and will be discussed later. Finally, the correlation of period with colour for all the sample is shown in Figure 12. There is a considerable scatter within each sequence (ab or c) in this diagram, due both to the stars lying away from the HB (flagged) and to the inclusion of data of poorer quality. The complete data set has been used here, and in the three previous figures to illustrate the overall characteristics. Selection of only first quality photometry leads to improved correlations as shown in Figures 13 to 16. In the CMD of Figure 13, non-variable blue HB (BHB) stars have been included to delineate the blue edge of the strip. The B amplitude - log P′ relationship in Figure 14 also shows schematically the mean locations of the RR Lyraes in M3

Figure 12. The period-colour relation for the complete B,V sample. The c-types (open circles) and ab-types (filled circles) define two distinct relations, separated by Δ log P = 0.125 because of their different mode of pulsation. Lines with the expected theoretical slope are added. Note how the flagged stars (Figure 9) lie off the mean relation, which can be understood because of their different luminosity.

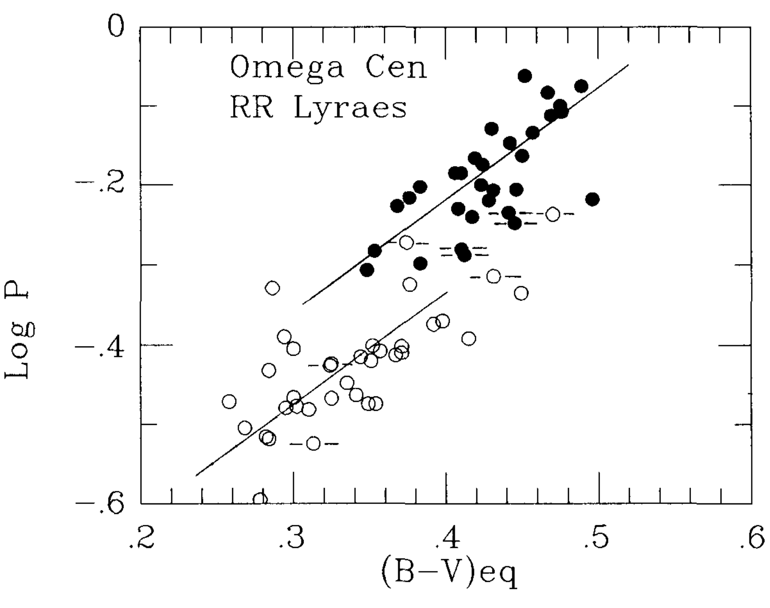

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Figure 13. RR Lyraes with the best (quality 1) photometry in the CMD, together with some of the non-variable BHB stars measured with high internal accuracy along with the variables. This pinpoints very precisely the blue edge of the instability strip.

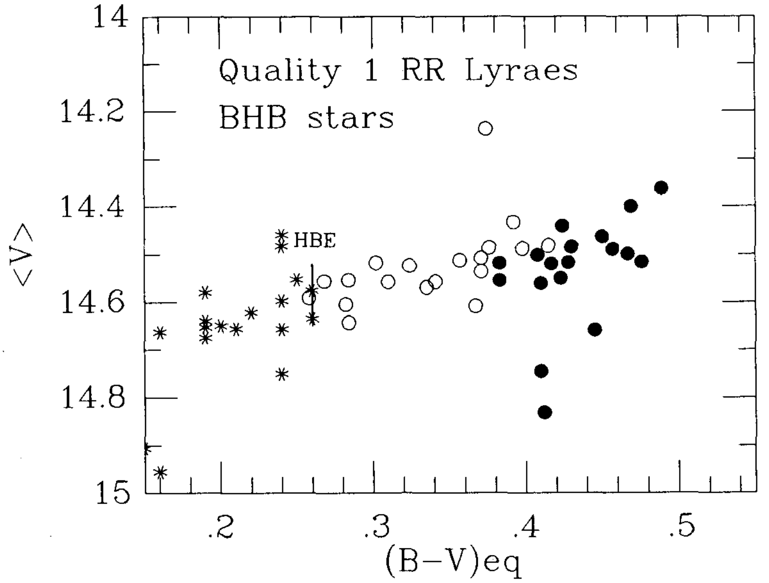

Figure 14. The blue amplitude-log P′ correlation for quality 1 data. The mean lines for M3 (Oosterhoff group I) and M15 (Oosterhoff group II) are indicated, showing that ωCen (group III?) is shifted further towards longer periods. The position of ωCen can be understood, at least in part, if the stars are more evolved, and therefore over-luminous with respect to the ZAHB (see text).

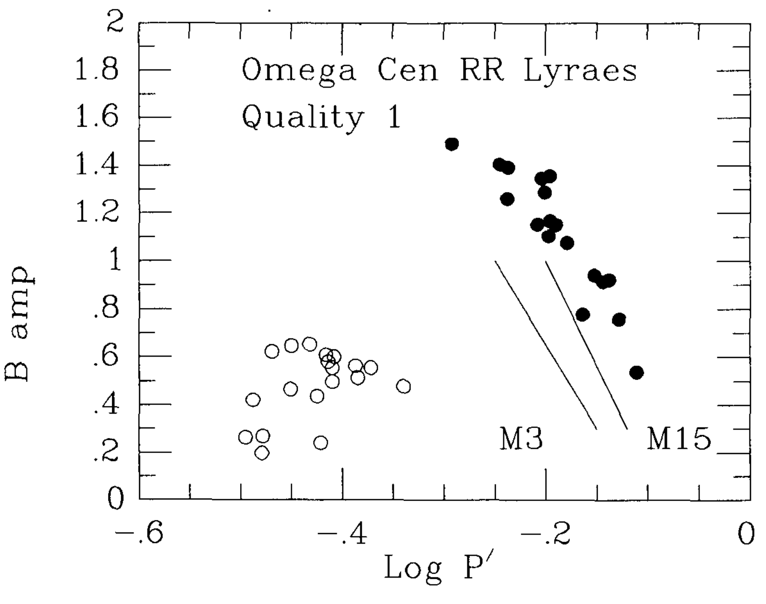

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Figure 15. The blue amplitude-colour relationship for stars with quality 1 photometry. The large range in amplitude among the ab-types persists, suggesting a non-unique relationship of amplitude with colour.

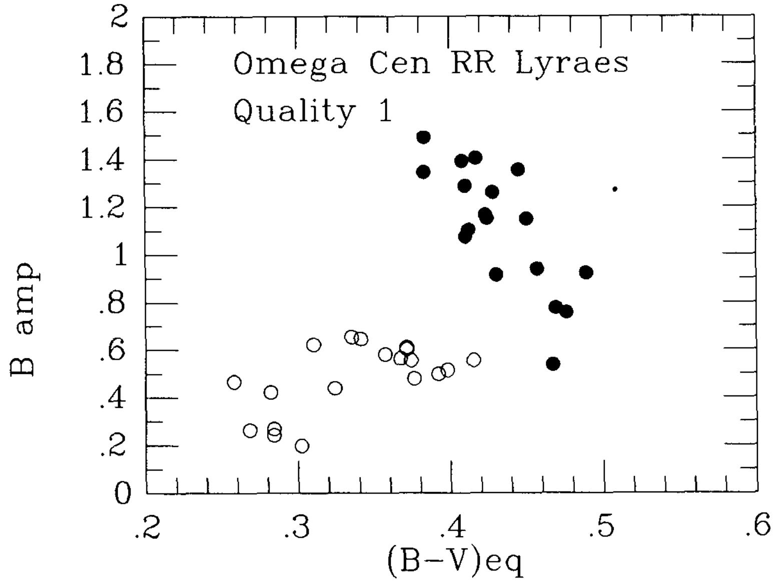
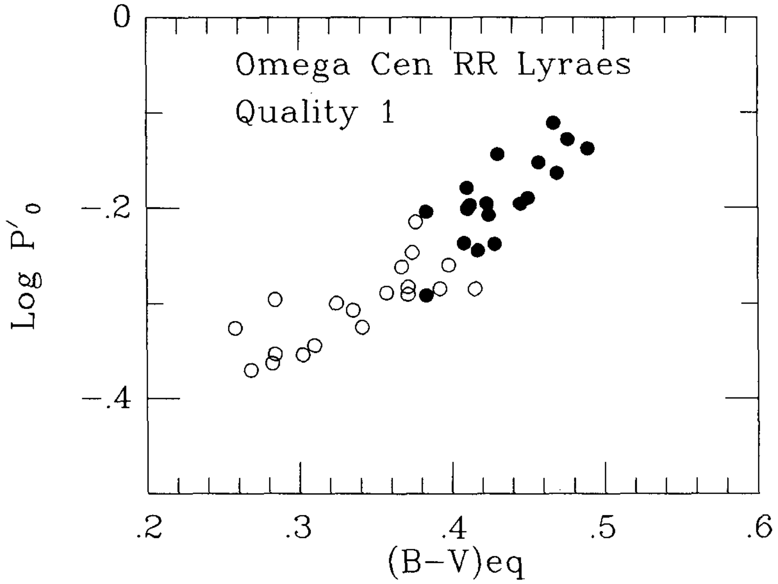


Figure 16. The (corrected, fundamental-mode) period-colour relationship for stars with quality 1 data. There is a hint that the c-types have a shallower slope than the ab-types. Most of the remaining spread in this diagram must be observational error, since the photolectric Walraven photometry, and (V-K) colours show a substantially smaller scatter.



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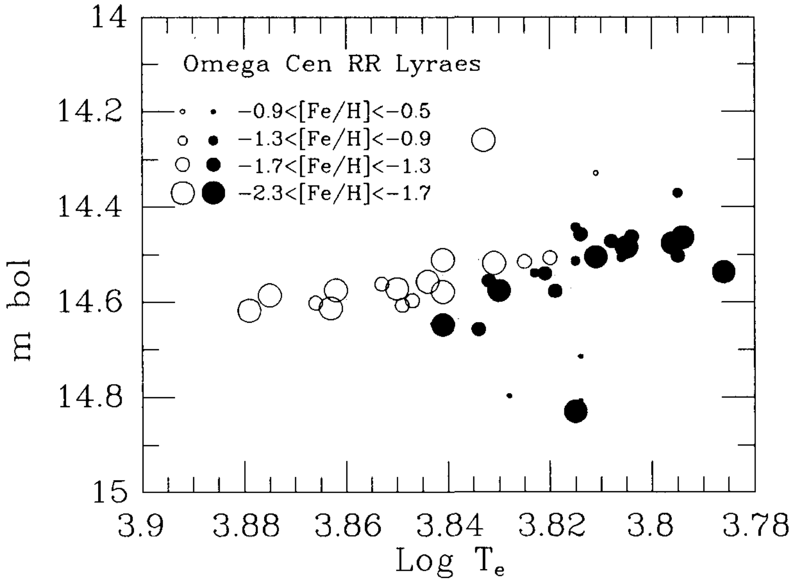
and M15 (Oosterhoff Groups I and II respectively). The B amplitude-colour, and period-colour relations of Figures 15 and 16 respectively retain the main characteristics of the full sample, but with somewhat reduced but still appreciable scatter. There is some suggestion of a difference in slope between ab and c types.

The next step required for the study of abundance groups in ωCen, comparison with other clusters, and in the derivation of physical parameters, is the conversion of colour to temperature. BDE used models calculated by Manduca using Bell-Gustafsson programs, and with the Doppler Broadening velocity, DBV = 3.6 km/s following Butler (1975). More recent model colours (but not specifically for RR Lyraes) are available by Kurucz (1981, see Lester et al. 1986) and VandenBerg & Bell (VdBB, 1985). A detailed comparison cannot be entered into here; for the BV data, we have used VdBB scales, which give temperatures in good agreement with those derived from the Walraven photometry (based on Kurucz 1981), but are about 150 to 200K cooler than BDE temperatures. Temperatures derived from infrared (V-K) colours (Longmore et al. 1989) are cooler still by about 100K.

The CMD for stars of different abundance groupings is shown in Figure 17. Most, but not all of the stars lying away from the main HB belong

Figure 17. This shows the position of those ωCen RR Lyraes with abundance data in the theoretical m_{bol} -log T_e diagram. Note that four of the five most metal-rich stars lie away from the bulk of the stars. There are otherwise no strong abundance-related effects apparent in the diagram.



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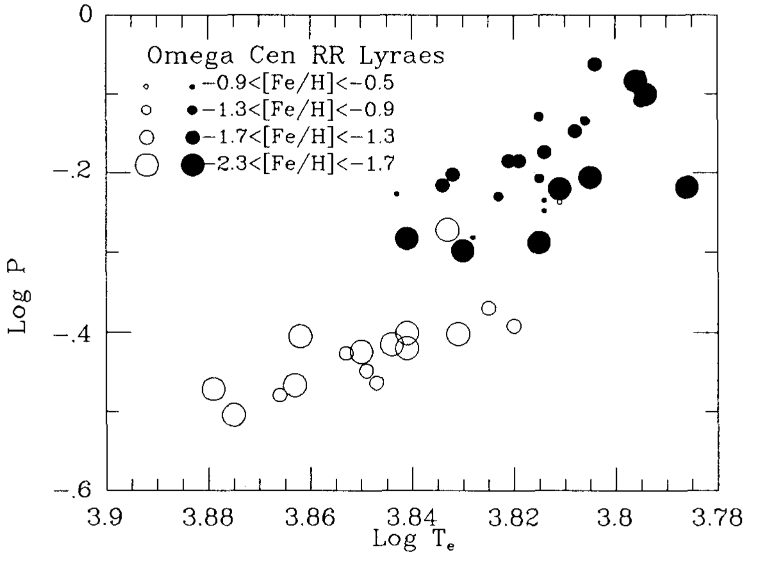
to the highest metallicity group. There is a small metallicity effect exhibited by the most metal-rich group in the period-colour diagram, at least among the ab-types, as shown in the log P-log T_e relationship of Figure 18. This effect is much smaller than that found in the period-temperature relationships of Oosterhoff I and II clusters covering a similar range of metallicity (e.g. see Bingham et al. 1984, Figure 24). In fact the effect may be even smaller, as a smaller spread in this diagram is found using temperatures from infrared colours (Longmore et al. 1989), and from the Walraven photometry (de Bruijn & Lub 1987). Clearly, as has been pointed out previously (e.g. Dickens 1982) the RR Lyraes in ωCen differ in some important property from those of comparable metallicity in other clusters. We shall return to this point later when discussing their evolutionary status, and the physical parameters (in particular the mass-to-light ratio) deduced from the period-temperature relation.

Figure 18. The log P - log T_e relationship for the abundance sample. Although some effect of the differing luminosity of the "extreme" stars (see Figure 9) can be detected, there is little if any "Oosterhoff effect" separating different abundance groups apparent for most of the sample. It is possible that some effect (less than that shown between clusters of different Oosterhoff groups) could be present, but masked by observational error. Note also the possibility of a smaller slope amongst the c-types.



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4 THE DISTANCE SCALE

The apparently small range in luminosity found amongst RR Lyrae variables has led to their extensive use as distance indicators in our own and nearby galaxies. Studies of their pulsation properties, and evolutionary status within clusters has opened up the prospect of a considerably greater precision in their use as distance calibrators. Similarly, refinement of the Baade-Wesselink and related methods of radius determination in field RR Lyraes has led to great improvements (see Moffett, this volume). Much interest now centres on understanding the dependence of luminosity on metallicity, as manifest in the Oosterhoff, or Sandage period-shift effect between clusters. Using a simple pulsation model, it is easy to show that a logarithmic relationship between period and temperature for a group of RR Lyraes (such as in a cluster) gives information about the mean mass-to-light ratio, M/L, so that a shift in such a relationship between clusters implies a difference in M/L. A full understanding of the pulsational and evolutionary properties of the RR Lyraes therefore holds the key to accurate distance calibration via M/L. This has received considerable attention in recent years, and is of great importance as it can in principle lead to improved cluster ages, via the more precise distance measurement. We concentrate here on the role the RR Lyraes in ωCen can play in these fundamental problems.

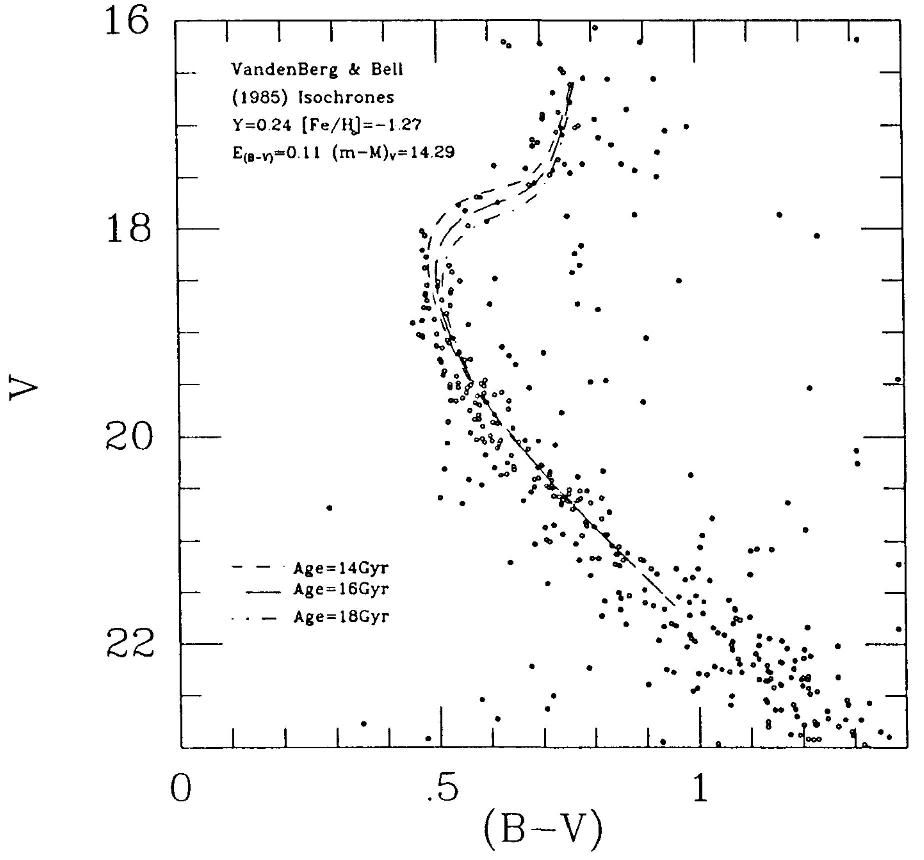
A classical, and essentially empirical method for finding distances to globular clusters comes from fitting their observed main sequences to nearby subdwarfs whose distances are known from their trigonometric parallaxes. This has been carried out by Noble & Dickens (1988) for a sample of clusters for which high accuracy CCD CMDs were then available. Although there have been more recent treatments of a greater number of clusters now available (e.g. Buonanno et al. 1988), the former study serves to illustrate the way in which RR Lyrae properties enter the problem, and how those in ωCen fit in to the picture.

Figure 19 shows the fit of three isochrones of different age, having roughly the mean metallicity of ωCen, and with the distance determined from the subdwarfs, to the ωCen data shown in Figure 7. The mean age around 16 Gyr agrees well with that found for the other clusters considered by Noble and Dickens. The subdwarf fit provides a calibration of the luminosity of the ωCen RR Lyraes, which is compared with the results for the other clusters in Figure 20. Note the weak correlation of M_V with [Fe/H], with ωCen not apparently conspicuous (within the errors indicated). I would like to make two remarks on this diagram.

Firstly, it provides a direct check (in principle) on the role of M_V in driving the Oosterhoff period shift between clusters, which Sandage (1982) demonstrated could be the dominant parameter correlating strongly with [Fe/H] over many clusters. Since it is M/L which must vary as the mean period-colour line shifts, our observed small range in M_V must imply a range of mass among the HB stars of the clusters in Figure 20 (i.e. assuming a similarly significant role in driving the period shifts). Although the estimated errors shown are too large to yet allow a definitive solution, it appears likely that some variation in mass exists amongst the clusters, in the sense of higher mass for the more metal-rich clusters. Note also that allowance for the effects of evolution away from the ZAHB, which will be more important for the metal-poorer clusters (see below) will tend to flatten the slope further.

Secondly, the variation of M_V with abundance **within** ωCen is also small, as illustrated in the CMD of Figure 17, with the same trend as shown in Figure 20. However the luminosity of any particular RR Lyrae is infuenced by its evolutionary history which needs to be considered before the argument can be developed further. This is discussed below in the context of searching for consistency with stellar evolution

Figure 19. The CMD of the main sequence and turnoff regions is shown, with three isochrones of different age superimposed. They have been fitted using the distance deduced from fitting to nearby subdwarfs, and provide a satisfactory mean representation of the data.



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models. However we can already see from the above how a very precise knowledge of the intricacies of RR Lyrae behaviour would enable the crucial precise calibration needed to determine cluster ages.

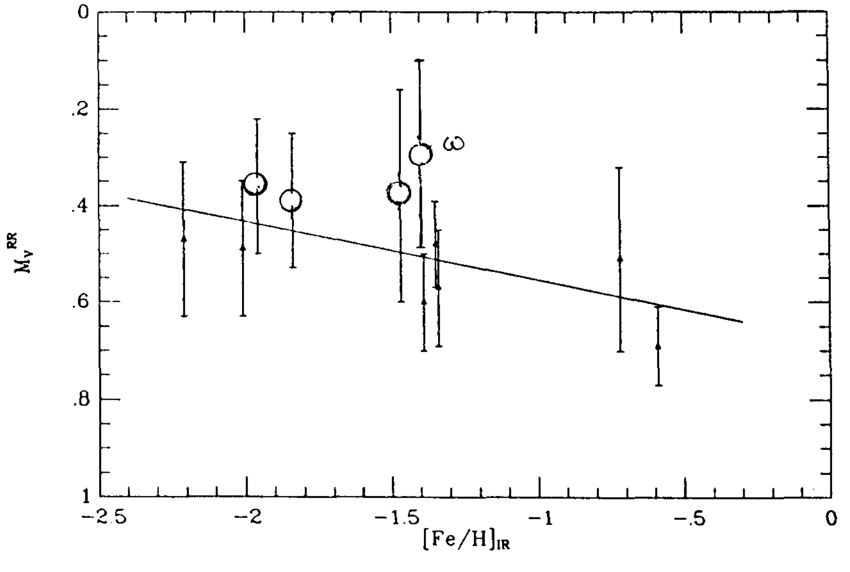
5 RR LYRAES AND STELLAR EVOLUTION

5.1 Evolution

Figure 21 shows the correlation of period shift with metallicity found by Noble & Dickens (1988), which has a slope of +0.079 ± 0.011, in excellent agreement with that of +0.084 found by de Bruijn & Lub (1987). These results are essentially consistent with the earlier result by Sandage (1982). Why is this effect so much smaller, if not absent altogether within ωCen? Also, Figure 14 shows that ωCen is shifted towards longer periods still than the Oosterhoff II cluster, M15, yet its average metallicity is much higher. Do these properties provide any clues as to the cause of the Oosterhoff effect?

As discussed by many authors, one can account for a systematic period shift, as found in the period-temperature relation, in terms of a variation in M/L between the clusters of each Oosterhoff group (or on a

Figure 20 A plot of the RR Lyrae luminosity, M_V, as a function of [Fe/H] for 10 clusters. A least-squares linear fit to these is shown, together with the result from the fit to ωCen. Note, however, that the four BHB clusters, shown as larger filled circles, are the most luminous, as would be expected if the stars populating the instability strip in these clusters are indeed more evolved, as discussed in the text. Allowance for this effect would give an even weaker correlation than shown.



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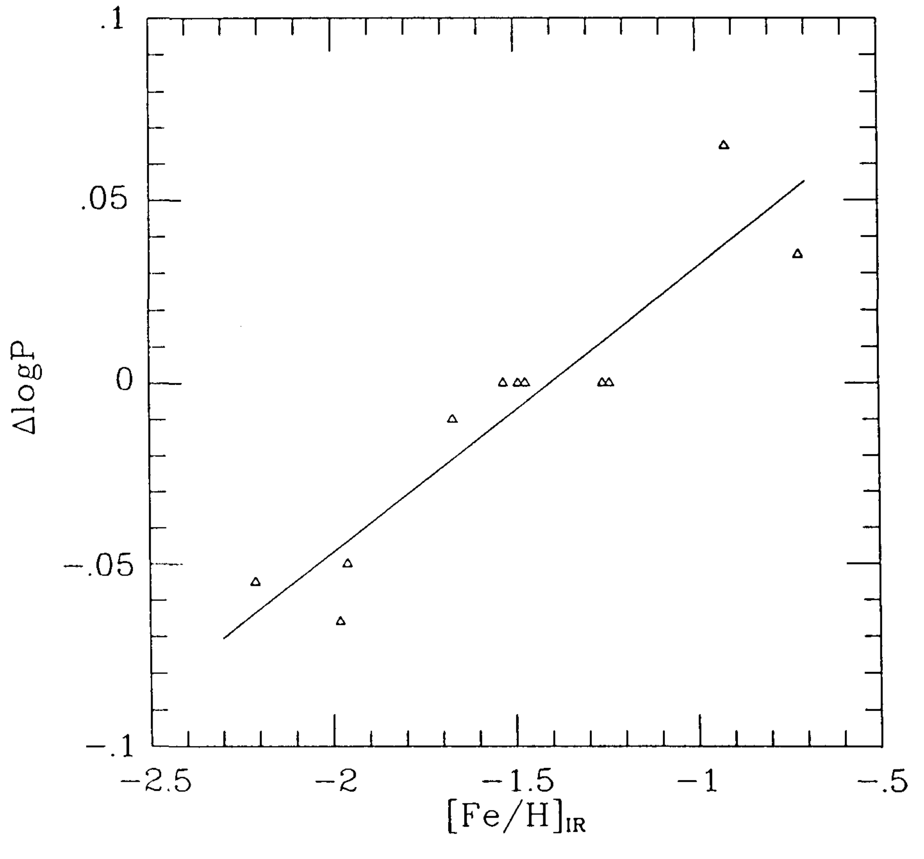
cluster-by-cluster basis). The "problem" is to be able to explain these differences, and now especially the correlation with metal abundance embodied in the "Sandage effect", in terms of stellar models. Furthermore, we should like to know how much of M and how much of L contribute to any given shift. (The current status of this entertaining pastime is discussed by Rood in this volume.) It turns out that the main contribution of ωCen to this problem is, however, merely to "explain" the anomalous position of ωCen itself!

A partial answer to the ωCen anomaly was proposed by Gratton et al. (1986) who considered the behaviour of the luminosities of HB models within the instability strip. They drew attention to the much smaller dependence of luminosity on metal abundance for evolved HB models than for those on the ZAHB. In clusters with very blue HBs, like ωCen and M92, most of the RR Lyraes are likely to be in a later stage of HB

Figure 21. The period shift - metallicity relation as derived by Noble and Dickens. The metallicity scale comes from infrared photometry by Frogel et al. (1983). The line is a least-squares fit to the data (see text).



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evolution than those in clusters with more red HBs (e.g. M15 and M3) and according to the models should hence show less correlation of luminosity with metals within the instability strip. This could account for the absence of any strong metal-dependent luminosity differences among the bulk of the RR Lyraes in ωCen (see Figure 17). Also, this luminosity excess would shift the bulk of the ωCen RR Lyraes towards longer periods as compared to ZAHB stars, of which there appear to be a sprinkling in ωCen (see the CMD of Figure 9). This could in principle account for the positive shift of ωCen with respect to M15, which must be dominated by stars near the ZAHB. Note, however, that the ωCen stars, being more evolved, will tend to have slightly higher masses than ZAHB stars, also affecting their position in the period-temperature plane, in the sense of reducing the shift with respect to M15!

Nevertheless we believe this picture to be essentially correct. It is indeed likely that the bulk of the RR Lyraes in ωCen are in an advanced stage of evolution. Figure 22 shows a representative CMD in which the data accurately represent the true relative distributions on the HB. Clearly the RR Lyraes account for only a few per cent of the HB, and must therefore mostly be evolving away from the ZAHB locations on the BHB. Comparison with other clusters, therefore, is inappropriate without taking account of evolutionary effects, and this has now been studied by Sandage elsewhere in this volume.

Thus ωCen has demonstrated the importance of evolutionary effects at least in clusters with extremely blue HBs. It is, however, likely that the morphology of evolutionary tracks (rather than just the ZAHB distribution) plays a significant role for **all** clusters in the details of just how the variables are distributed in the instability strip, and perhaps in their pulsational behaviour (e.g. double-mode pulsation, location and width of either/or regions). This topic has been discussed already in some detail by Bingham et al. (1984) in a comparison of the properties of the Oosterhoff I and II clusters, M3 and M15 respectively. The topic would, however, repay further study with detailed simulations using the latest HB model tracks.

5.2 Physical parameters

We now discuss briefly the derivation of physical parameters, derived from purely pulsational considerations, and their comparison with those expected from evolutionary models, thereby providing a powerful check on the theory. We include some preliminary mean results from our data, and show how they bear on current stellar evolutionary predictions. A full discussion of this topic is outside the scope of this paper, and will be given elsewhere (Dickens & Bingham 1989).

Firstly, the mean mass-to-light ratio, M/L is derived by fitting the de Bruijn and Lub slope of -3.48 to the data in Figure 18. This slope is also the theoretical slope derived by van Albada & Baker (1971) and provides an acceptable fit to our data. This gives a mean value of

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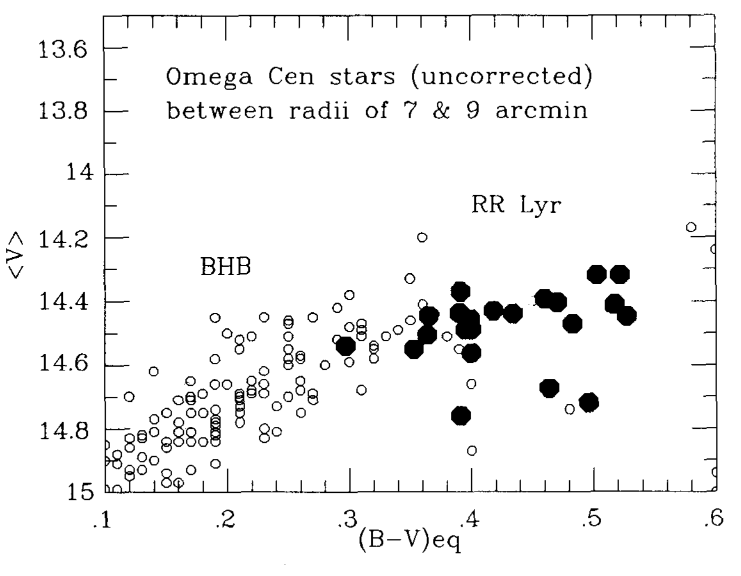
$$\langle \log(M^{0.81}/L) \rangle = -1.88 \quad = A_{puls}$$

in exact agreement with that of -1.88 +/- 0.03 obtained by de Bruijn & Lub. A second result often derived from cluster RR Lyrae properties is the helium content, Y, using the temperature of the blue edge or the width of the instability strip. From Figures 13 and 18, we find $\log T_e(\text{hbe}) = 3.875$ at $\log P_1 = -0.525$, which from Tuggle & Iben (1972) implies Y = 0.28. More recent work by Stellingwerf (1984) has, however, cast doubt on this method. His convective blue edges show little sensitivity to Y, with $\log T_e(\text{hbe}) = 3.856$ (Y = 0.2) and $\log T_e(\text{hbe}) = 3.862$ (Y = 0.3). More theoretical work is needed to explore this further. However it is interesting to note that the cooler temperature scale from V-K would give better agreement with Stellingwerf's blue edges.

The above mass-to-light ratio may be combined with the luminosity of the RR Lyraes derived from the main-sequence distance calibration used for Figure 7 to derive a mean mass for the RR Lyraes. The distance modulus derived, using the original Lutz-Kelker corrections to the subdwarf parallaxes (see Carney 1979), is (m-M) = 14.29, or applying one half the corrections (e.g. see Hesser et al. 1987) gives $M_V(\text{RR}) = 0.30$ magnitude.

Figure 22. CMD of a statistically true representative sample of RR Lyraes and non-variable stars, showing the continuous distribution with colour expected if the RR Lyraes are evolving away from their ZAHB locations on the BHB. The RR Lyrae data have not been corrected for radial photometric error, which becomes important inside 10 arcmin radius, in order to match the colours of the non-variable stars.



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Thus log $L_{RR}/L_\odot$ = 1.77 which combined with the above mass-to-light ratio yields a mass of $M_{RR}/M_\odot$ = 0.73. Are these values in accord with HB models? For Sweigart-Gross (1976, SG) models near the ZAHB, the mass-to-light ratio is given roughly by (see Bingham et al. 1984, equation 11)

$$\log(M^{0.81}/L)_{evol} = -1.40\ (Y - 0.3) - 1.87 = A_{evol}$$

which implies Y = 0.3 for A_{puls} = -1.88. The primordial value of Y = 0.23 requires A_{evol} = -1.77, implying a mass around 0.90 $M_\odot$ for log L = 1.77 from the main-sequence fit, as compared to the pulsation mass of 0.73. If the ωCen RR Lyraes are in an advanced stage of evolution, as suggested above, then the appropriate log L_{evol} is about 0.1 fainter, and M = 0.75 $M_\odot$ for log L_{zahb} = 1.67, which agrees with that derived from pulsation considerations. Thus only by postulating that the ωCen RR Lyraes are in an advanced, more luminous stage of evolution can we reconcile pulsation theory, and the main sequence calibration with evolution theory, but this is a plausible and encouraging result.

Also note that about two-thirds of the discrepancy in luminosity (at constant mass) between pulsational and evolutionary values found by Bingham et al. for M15 (where the RR Lyraes must mainly be near the ZAHB) is removed with the revised B,V temperature scale used here, or entirely removed using the V-K calibration. This underlines the crucial importance accurate temperature scales have in this method of evaluating the validity of evolutionary models of the HB, and in the derivation of mass and luminosity from pulsation studies.

6 CONCLUDING REMARKS

So what have we learned from studying ωCen, and what further should be done? Although we seem to be no nearer understanding why ωCen is the way it is, the properties of its sub-populations over the whole HR diagram are broadly understandable in terms of an overall range in heavy-element abundance. We leave to one side the more complex role of mixing, especially in the red giant stars, which has recently been discussed by Dickens & Caldwell (1988).

Whilst we have no real understanding of the phenomenon, the size and shape of the abundance distribution appears to be similar for stars in the various stages of evolution observed, and could be caused by two dominant underlying populations of different mean metallicity. The observed pulsational properties (i.e. the period-amplitude-colour-luminosity correlations) of the bulk of the RR Lyraes are qualitatively the same as those in other clusters (as expected), but the sub-populations do not behave as those in other clusters of different metallicity, in showing a strong Oosterhoff effect. This is thought to be due to their advanced stage of evolution; the few RR Lyraes in clusters like M13, M92 are likely to be similarly over-luminous through advanced evolution, and this must be taken account of in comparative studies of the Oosterhoff effect. The mean mass and luminosity of the

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RR Lyraes derived from pulsation theory and calibration of the cluster distance, are consistent with those expected from SG HB models, with preferred values of $M/M_\odot$ = 0.73, $\log(L/L_\odot)$ = 1.77 (M_V = 0.30), with estimated uncertainties of a few hundredths in each case. This is encouraging for the theory but greater precision is still needed for a definitive result, both to test the theory, and to provide better distance calibration.

Great effort is still needed to improve further the T_e-colour calibrations, and to extend the evolutionary tracks beyond core helium exhaustion to check the advanced evolution picture for ωCen RR Lyraes - the lack of much luminosity difference as a function of abundance, if reflected in the models is a powerful qualitative check, and the pulsation parameters a powerful quantitative check. Spectra of good samples of subgiants, stars at turnoff and on the main sequence are needed to verify the abundance spread postulated from the photometry.

One disappointing aspect of the study of the ωCen RR Lyraes concerns the solution of the Oosterhoff problem, since it was to be hoped that the occurrence of what appeared to be different Oosterhoff groups within one cluster would enable a direct check on their relative luminosities, and perhaps give some indication which are the important parameters driving the period shifts in other clusters. As demonstrated elsewhere in this volume, in spite of considering in detail the effects of evolution (Sandage), and recent model developments (Rood), this problem is yet to be solved. Although we have known for a long time that mass, luminosity, and track morphology must play a role, we still need to know precisely what the values are, and which other parameters also enter, so that we can use our knowledge effectively in the various fundamental applications that have been referred to.

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