ON THE INTERPRETATION OF RR LYRAE PROPERTIES IN GLOBULAR CLUSTERS AND IN OTHER POPULATION II SYSTEMS

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Abstract. The differences in observational parameters of the RR Lyrae variables and horizontal branch stars of globular clusters and other population II systems are considered. A discontinuous behaviour of some parameters is outlined. The Oosterhoff dichotomy and the HB morphology are discussed with regard to a conjecture of mass loss in the pre-HB phase.

1. Introduction

The main problem concerning Population II systems is to determine the age and the helium abundance of each of them. Knowledge of these parameters for a large number of Population II systems has important consequences for cosmology (e.g. the interpretation of the Hubble time, the problem of the helium genesis, the formation of galaxies, and in particular of our own Galaxy and its early chemical evolution).

Unfortunately, the absolute determinations of age and helium abundance from the theory of stellar evolution involve serious difficulties. At present, the uncertainty in age can be estimated to be about 40% when the uncertainty in the theoretical models is also taken into account (Renzini, 1971). The situation regarding the determination of the helium content is no better. Available estimates of $Y=0.29\pm0.03$ for globular clusters (e.g. Iben, 1971) are based on HB evolutionary models with improper fitting conditions at the boundary of the convective cores.

The existence of a semiconvective region surrounding the fully convective core (Schwarzschild, 1970; Castellani *et al.*, 1971; Demarque and Mengel, 1972) nearly doubles the core helium-burning lifetime. This fact leads to a helium abundance of about 0.15 (using the same procedure as Iben, see also Demarque *et al.*, 1972). Moreover, since recent computations of red giant evolutionary models (Rood, 1972) lead to RG lifetimes shorter than previous values by about 15 or 20%, the estimated helium abundance is further reduced by about 0.03.

Therefore, in our opinion, a standard error of ±0.03 in the helium determination is a rather optimistic estimate. Owing to uncertainties in opacity, mass of the helium core at the flash, treatment of semiconvection and stellar counts, we believe that at present the uncertainty in the determination of the helium content of Population II

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stars might even be ±0.15. This latter estimate still allows the possibility of a high helium content ($Y \simeq 0.30$).

The failure of accurate *absolute* determinations of age and helium abundance of globular cluster stars emphasizes the importance of *relative* determinations of these parameters. This procedure should enable us to answer the question "how large, if any, are age and helium differences among the various Population II systems?".

Within this framework it becomes particularly important to consider the differences in the observational parameters of the Population II systems. In fact there is a popular tendency to assign to all the galactic globular clusters the same age and the same helium content, in spite of the growing evidence that something else besides the metal content varies from cluster to cluster (van den Bergh, 1967; Sandage and Wildey, 1967; Hartwick, 1968; Castellani *et al.*, 1970; King, 1971; Dickens, 1972). Therefore, we cannot rule out the possibility that the Population II systems have different ages and/or helium contents, at least until both observation and theory prove that the relative abundances of metals are the so called 'second parameter' (e.g. Z_{CNO}/Z).

This communication is an account of a rather larger paper in preparation (hereinafter referred to as CGR 72) dealing with the interpretation of observed differences among Population II systems. We now wish to discuss the problem of the well-known Oosterhoff dichotomy in relation to the morphology of the horizontal branches of globular clusters and related systems. Indeed, a 'good theory' should succeed in explaining RR Lyrae properties and HB morphologies at the same time.

Observational evidence concerning RR Lyrae variables can be used in the framework of pulsation theory. However, according to the current literature, many possible explanations of the observations (e.g. the Oosterhoff effect) exist. On the other hand, observed morphologies of horizontal branches can be related to evolution theory. However, even in this case some ambiguities remain.

When the requirements corresponding to the two separate attempts are fitted together, a number of possible explanations have to be ruled out because they don't fit either the pulsation theory or the HB evolution theory. Some remaining ambiguities can be removed when the results of the evolution prior to the HB phase and the present knowledge and belief about the process of formation of globular clusters and related systems are considered.

It may be that the procedure just described is not yet able to eliminate all the ambiguities and to yield firm conclusions because of observational and theoretical uncertainties. However such an approach might assist in clarifying the problem and suggest which observations and computations will be the more important.

Furthermore, we feel that a fully quantitative theory is not quite meaningful at present and that a qualitative, or a semi-quantitative, approach is preferable. For instance, one has that, according to pulsation theory, the difference in the mean period of the *ab*-type variables between the two Oosterhoff groups may be ascribed to a luminosity difference $\Delta \log L \simeq 0.1$, or to a mass difference $\Delta \log M \simeq -0.1$ or to a difference in the mean effective temperature $\Delta \log T_{\mathrm{eff}} \simeq -0.02$ (corresponding to $\Delta(B-V) \simeq 0.07$), or, finally, to a combination of these three quantities. It is also worthwhile to note that the foregoing numbers are very close (particularly in the first two cases) to the uncertainties which affect any direct determination of absolute luminosities, masses and colours of HB stars.

In the following we shall emphasize in the whole pattern of the observations: (i) continuity or discontinuity in the observed parameters and, (ii) morphology of the horizontal branches, i.e. we shall be concerned with the topological properties of the observations. From a theoretical point of view, we shall try to find a theoretical scheme topologically analogous to the observational picture.

2. Observational Evcidence for the RR Lyrae Variables in Galactic Globular Clusters

In this section the most relevant charecteristics of the so called Oosterhoff effect are summarized. A longer discussion will appear in CGR 72.

In passing from one Oosterhoff group to the other, we have tried to determine whether each observational parameter changes continuously or discontinuously. In the latter case, the amont of the discontinuity was obtained on the basis of the distribution of the available observational data (rather than as a difference between the mean values corresponding to the two Oosterhoff groups). Bearing this procedure in mind we have the following indications:

(i) The mean period of the *ab*-type variables suffers a discontinuity $\Delta\langle \log P_{ab} \simeq 0.07$ (see Figures 1 and 2).

(ii) The mean 'fundamental period – the mean period of all the RR Lyrae variables in a cluster when the periods of the *c*-type variables are transformed to the fundamental

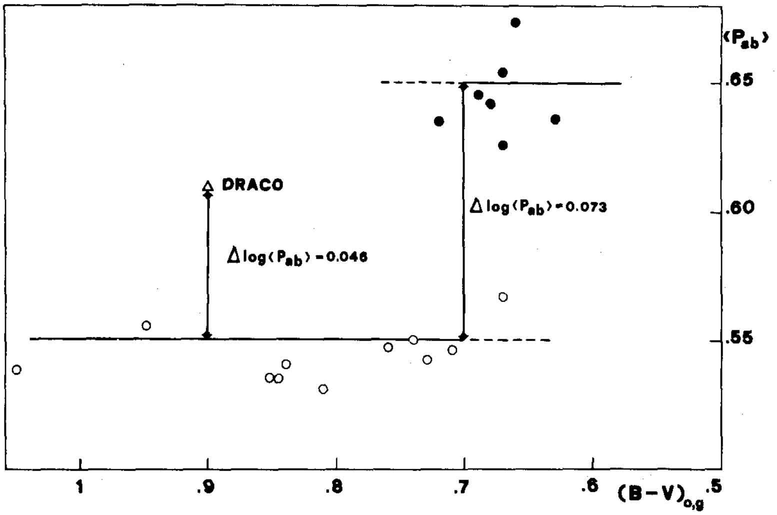

Fig. 1. The mean period of the *ab*-type variables of Oosterhoff type I and II clusters and of the Draco system is plotted against $(B-V)_{0,g}$. Differences in $\Delta \log \langle P_{ab} \rangle$ between the two Oosterhoff groups and with respect to Draco are also indicated.

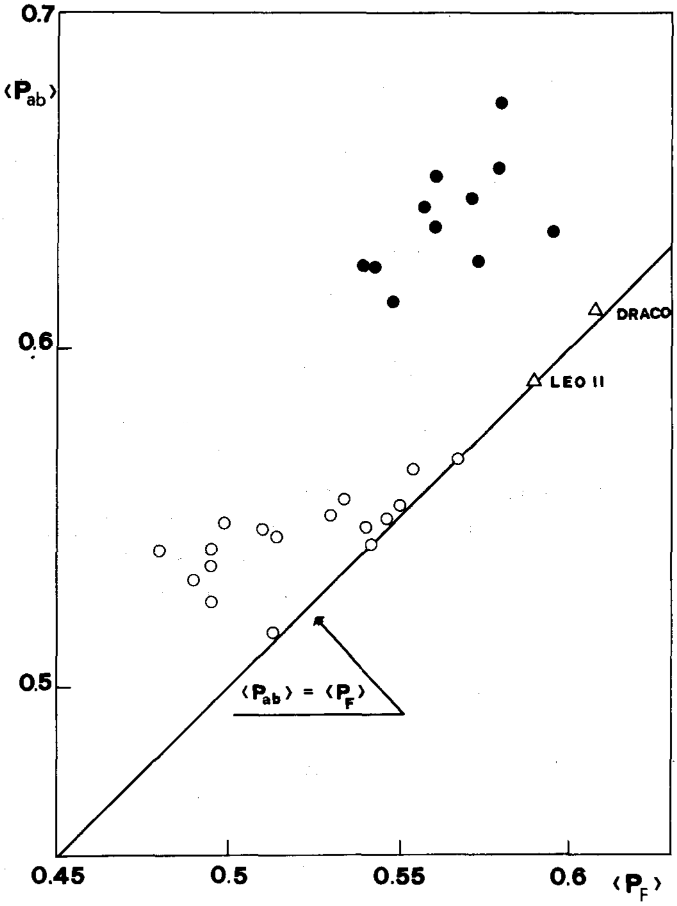

Fig. 2. The mean period of the *ab*-type variables of Oosterhoff type I and II clusters and of the dwarf galaxies Draco and Leo II is plotted against the fundamental period (see text).

period – turns out to be continuous, i.e. $\Delta\langle\log P_F\rangle \simeq 0$ (see Figure 2). A discussion of the incidence of some selection effects will appear in CGR 72.

(iii) The transition period – the shortest period of the *ab*-type variables in a cluster (in some cases very poorly determined) – may be discontinuous by $\Delta \log P_{tr} \lesssim 0.07$.

(iv) The median period – the period of a variable lying just in the middle of the instability strip – may be discontinuous by $\Delta \log \tilde{P} \lesssim 0.07$.

(v) The relative number of the *c*-type variables to the *ab*-type variables is discontinuous by $\Delta(n_c/n_{ab}) \simeq 0.5$, if one excludes three clusters classified as CII (Castellani *et al.*, 1970).

(vi) The instability strip seems to be populated uniformly in type II clusters, whereas there is a strong departure from uniformity in type I clusters (see CGR 72).

(vii) No significant trend in $\langle\log P_{ab}\rangle$ is seen within each Oosterhoff group (see for instance Figure 2 and Figure 5 in Castellani *et al.*, (1970)). This means that very likely

$\partial\langle\log P_{ab}\rangle/\partial\log Z \simeq 0$. A similar statement must hold for the dependence of $\langle\log P_{ab}\rangle$ upon a possible 'second parameter'.

On the basis of the foregoing considerations, it seems possible to conclude that a real discontinuity, rather than a difference between two widely separate classes of objects, exists between the two Oosterhoff groups.

3. The HB Morphology and Evolution

Dickens (1972) classifies the morphological appearance of the horizontal branches of globular clusters into seven classes according to the colour distribution of the HB stars. Dickens' class 1 corresponds to a completely blue HB, without RR Lyrae variables or red HB stars (prototype M13). Dickens' class 7 corresponds to a stubby red HB as in 47 Tuc. Oosterhoff type II clusters are confined essentially to Dickens' classes 2 and 3, whereas Oosterhoff type I clusters are contained in Dickens' classes 3 to 6.

It turns out that all the Oosterhoff type II clusters have horizontal branches well populated on their blue sides and lacking or only poorly populated on their red sides. On the contrary, the Oosterhoff type I clusters always have at least some red HB stars and exhibit an extremely variable population on the HB blue side (compare for instance M5 and NGC 362).

At first sight it is rather surprising that the clusters in Dickens' class 1 are, on the average, more metal-rich than the clusters in class 2 and more metal-poor than the clusters in class 3 and in the further ones. The meaning of the Dickens classification should be the following. In passing from the Oosterhoff type II clusters to clusters like 47 Tuc, at increasing metal abundances, the well populated part of the HB moves first to bluer colours, leaving a depopulated instability strip. Then, by further increasing the metal abundance, the blue end of the HB becomes even bluer or remains fixed; the instability strip and the red side of the HB begin to be populated. The increasing population of the red side of the HB is not accomplished by a shift of the well populated part of the HB towards the red, but by a progressive depopulation of the blue side. Eventually, no blue HB star remains and one has a stubby red HB.

It is well known that considerable difficulties are encountered when one tries to fit the observed horizontal branches with the available evolutionary tracks. This holds even if semiconvection effects are taken into account, and in particular if one assumes a constant stellar mass evolving from the main sequence to the HB.

The most relevant of these difficulties are the following:

(i) The bluest HB stars are not fitted by stellar models unless ages are exceedingly large.

(ii) The effective temperature range of the slowly travelled parts of the evolutionary tracks is usually too small compared with the observed range of HB colours.

(iii) Single evolutionary lines don't usually fit the observed gradients in the effective temperature distribution of the stars along the HB.

(iv) If only the metal content is allowed to change from cluster to cluster, it is not possible to reproduce all the observed features of the horizontal branches.

One way out of these difficulties is to reject the theoretical evolutionary tracks computed up to now, and to hope that the fitting will improve with better input physics. The second way is to relax some of the foregoing assumptions, eventually allowing for some spread in the stellar parameters and for some mass loss prior to the HB phase.

Although a certain spread in chemical composition or in helium-core mass among the HB stars in a cluster may perhaps produce analogous effects, the simplest assumption seems to be that of allowing for a loss of mass in the pre-HB phase. In this case, the bluest HB stars can be fitted (Castellani and Renzini, 1968). If some spread in the mass loss for the HB stars of a cluster is also assumed, it is not difficult to account for the observed range of effective temperatures (Iben and Rood, 1970; Castellani *et al.*, 1970; Iben, 1971, 1972).

In this framework, point (iii) seems to require different HB mass functions in different clusters, and point (iv) indicates that the mean amount of the mass loss in a cluster must be very sensitive to the metal abundance and to the 'second parameter'.

This set of assumptions will be referred to in the following as 'the mass loss conjecture'. In the subsequent section, the consequences of the mass loss conjecture will be compared with the requirements concerning the behaviour of the HB parameters induced by considering the Oosterhoff effect.

4. The Oosterhoff Effect and the HB Morphology

According to pulsation theory, the discontinuity in $\langle P_{ab} \rangle$ between the two Oosterhoff groups implies a discontinuity either in the mean luminosity of the *ab*-type RR Lyrae variables, or in their mean mass, or in their mean effective temperature, or finally a more sophisticated combination of $\Delta \langle \log L \rangle$, $\Delta \langle \log M \rangle$ and $\Delta \langle \log T_{\mathrm{eff}} \rangle$.

If one follows the mass loss conjecture (or more generally assumes a certain range in the HB stellar parameters) it turns out that a discontinuity between the two Oosterhoff groups must occur in at least one of the mean values of the four parameters which control the HB evolution (Z, Y, M_{core} and M). In the following we shall discuss in some detail the four simplest possibilities, i.e. the discontinuity in $\langle P_{ab} \rangle$ is due to a discontinuity in Z, or in Y, or in M_{core}, or finally in M. Furthermore, a discontinuity in some of these four parameters may be due either to an initial difference in age or chemical composition between the two Oosterhoff groups, or to the existence of some threshold mechanism operating during the pre-HB evolution.

A discontinuity in Z can be ruled out on two grounds. The observational evidence indicates that, actually, metallicity varies continuously in passing from one Oosterhoff group to the other; the mean period of the *ab*-type RR Lyrae variables appears to be independent of metallicity within an Oosterhoff group.

A discontinuity in Y might be due either to an initial difference in the helium content, or to some threshold mechanism for a partial mixing of the superficial stellar layers. Very little can be said about the first possibility; up to date pre-HB evolutionary computations seem to exclude the second eventuality.

A discontinuity in M_{core} has been considered for some time as a possibility related to the nitrogen flash. However, recent computations of the cross-section for the nitrogen α-capture (Couch, *et al.*, 1972) exclude the possibility of the nitrogen flash actually occurring. Therefore it seems very unlikely that a discontinuity in M_{core} is the cause of the Oosterhoff dichotomy.

The possibility of a discontinuity in the stellar mass is in accordance with the mass loss conjecture. A threshold mechanism for the mass loss should only act for stars with stellar parameters in a certain range. Then a 'critical boundary' should mark the transition corresponding to the discontinuity in the amount of mass loss.

It is quite natural to locate this hypothetical threshold mechanism at the helium flash. The discontinuous mass loss occurring at the flash might be superposed on a steady loss of matter taking place during the red giant evolution. Very likely the stars in a cluster are not strictly identical; core rotation, magnetic fields, chemical differences could lead to a certain range of core and stellar masses at the helium flash.

As a result, stars at the flash would be characterized by a finite dispersion in a diagram with pertinent stellar parameters as coordinate axes. A variety of different situations can then arise according to the relative position of the group of representative star points and of the critical boundary. In Figure 3 are plotted the morphologies

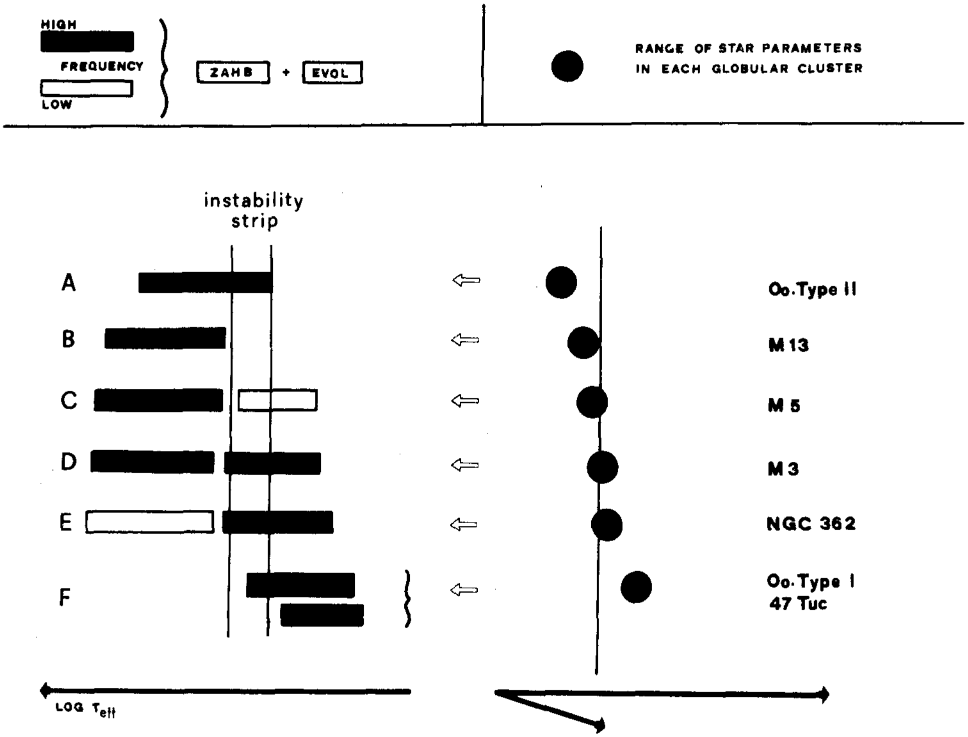

Fig. 3. Schematic morphologies in the HR diagram of horizontal branches of globular clusters (left-hand panel). They are related to the relative locations in a pertinent diagram of representative star points and of the 'critical boundary' for the occurrence of mass loss (right-hand panel).

of the horizontal branches as they result from various cases, schematically represented by the mutual locations of stars of a cluster (circles) and of the critical boundary (vertical straight line).

In case A, all the stars in the cluster suffer a sudden mass loss; correspondingly the slowly travelled part of the HB is blue as in the clusters in Dickens' class 2. For an increasing metal abundance one would expect an increasing mass loss (the surface gravity is smaller along the red giant branch). The HB evolutionary tracks shift to bluer colours and move out of the instability strip (case B, as in Dickens' class 1). When the metal abundance increases further, a few stars begin to cross the critical boundary. Then the threshold mechanism ceases to act for them; they do not lose mass, and they start to populate the red side of the HB and the instability strip. On the other hand, most of the stars continue to lose mass and to populate the blue side of the HB (case C). This situation corresponds to Dickens' class 3, whose prototype is M5.

As the sample of representative star points is shifted across the critical boundary because of increasing metal abundance, more and more stars stop losing mass. Correspondingly, the HB appears to be populated more and more uniformly on both sides of the instability strip (case D, resembling Dickens' class 4 with prototype M3). Continuing the trend already outlined, when only a few stars still lose matter, there is a progressive depopulation of the blue side of the HB in favour of the red side and the instability strip (case E, corresponding to Dickens' classes 5 and 6). Finally, no stars undergo mass loss by means of the threshold mechanism, and one has only a red HB with few or no RR Lyrae variables (mostly *ab*-type). This situation (case *F*) corresponds to Dickens' class 7, whose prototype is 47 Tuc.

With regard to the Oosterhoff effect, case A corresponds to Oosterhoff type II clusters, cases C, D, E, and in part F, correspond to Oosterhoff type I clusters. The foregoing picture then reproduces quite closely the observational evidence that the Oosterhoff type II clusters always have blue horizontal branches, whereas the Oosterhoff type I clusters exhibit a large variety of HB morphologies. In this scheme, the discontinuity in the mean period of the *ab*-type variables between the two Oosterhoff groups is due primarily to a mass difference ($\Delta \log M \simeq -0.1$, according to pulsation theory). However, this mass difference could be smaller if the mechanism proposed by van Albada and Baker (1972) is actually operating.

Up to now we have assumed that globular clusters form a unique sequence. Actually this is not the case. Clusters believed to have the same metal content have in many cases quite different HB morphologies. On the other hand, clusters believed to be rather metal-different exhibit similar HB morphologies. This fact is related to the 'second parameter' puzzle.

The hypothetical threshold mechanism for the mass loss could act as an 'amplifier' of small differences in the parameters other than the metal content. Indeed it is very likely that the helium flash phenomenon depends primarily on the core mass. An equal difference in the core mass is produced either by a factor ten in the metal content, or by a difference of about 0.05 in the helium content (Rood, 1972). Therefore, if the helium abundance is the second parameter, a difference $\Delta Y \lesssim 0.05$ among the globular clusters is sufficient to lead to rather large effects as far as the HB morphology is concerned.

As is well known, the dwarf galaxies Draco and Leo II show a mean period of the *ab*-type variables intermediate between those of the two Oosterhoff groups. In Figure 2 Draco and Leo II lie in a region which is lacking in galactic globular clusters. This means that an intrinsic parameter (constant in the clusters) has different values in the two galaxies.

An age difference of a few billion years could explain the strange behaviour of the RR Lyrae variables in these two latter systems. Indeed, the HB mass decreases secularly at a rate of about 2 percent per billion years because of evolutionary effects. As a consequence of that, the zero-age HB location shifts bluewards at a rate of about $\Delta \log T_{\text{eff}} \simeq 0.02$ per billion years. Correspondingly, the part of the instability strip where long period variables are located is depopulated and the mean period decreases. In order to have the observed value of $\langle P_{ab} \rangle$, it would be sufficient if Draco and Leo II were younger than the galactic globular clusters by about 1 to 3 billion years.

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DISCUSSION

van den Bergh: Available evidence suggests that the rate of star formation in a Galaxy $\sim \varrho^n$, in which ϱ is the initial gas density. This explains why *E* galaxies, in which ϱ is high contain mostly old stars. Irregular galaxies, which have a low mean density, have not yet used up all their interstellar gas and consequently contain many young stars. The mean density of dwarf spheroidal galaxies is even lower than that in irregulars. This seems to conflict with the observation that dwarf spheroidals contain only old stars. This suggests that dwarf spheroidals were not formed as individuals but were created together with giant galaxies. Observations of the distribution of dwarf spheroidals in the M81 group, the South Pole Group and the Local Group give strong support to the idea that dwarf spheroidals are associated with giants. Presumably this implies that the dwarf spheroidals formed (like globular clusters) during the collapse of the giant galaxy with which they are associated. On such a picture the age difference between the Draco System and the Galaxy cannot exceed the collapse time-scale of the Galaxy, which is only a few times 10^8 yr. It seems doubtful if such a small age difference can account for the differences that are observed between the dwarf spheroidal satellites of the Galaxy and galactic globular clusters.

Renzini: What I wanted to show is that the distribution of stars along the horizontal branch may be rather sensitive to age. An age difference of 1 to 3 billion years would produce the observed difference in $\langle P_{ab} \rangle$ between the Leo II and Draco systems on the one hand and the galactic globular clusters of Oosterhoff type I on the other hand. Nevertheless, this age difference is only a *sufficient,* not a *necessary,* condition. It may be that a difference in some other parameter is responsible for the strange values of $\langle P_{ab} \rangle$ in the two dwarf galaxies. However, this hypothetical parameter cannot be the same 'second parameter' invoked for the galactic globular clusters, otherwise no dichotomy would be observed in $\langle P_{ab} \rangle$ among the globular clusters.

Demarque: Are you appealing to small differences in helium content from cluster to cluster, or from star to star within the cluster?

Renzini: What I appeal to within one cluster is a certain range in the stellar parameters, more likely due to different core rotations. A range in helium among the stars in one cluster cannot be excluded, but I don't strictly require that. A small range in helium from cluster to cluster would instead be responsible for the different appearance in horizontal branches in clusters with about the same metal content.