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THE AGE OF GALACTIC GLOBULAR CLUSTERS

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RESUMO. O problema da determinação da idade dos aglomerados globulares galácticos é focalizado, discutindo-se as possíveis fontes de erros e indeterminações. O papel das variáveis RRLyrae é discutido dentro do quadro evolutivo geral. A aplicação de um método de ajuste geral para os aglomerados globulares galácticos M15 e M4 fornece, respectivamente

$t=(13\pm3)\cdot10^9$ anos e $t=(12.2\pm0.2)\cdot10^9$ anos.

Sugestões para uma idade similar ao aglomerado M3 são colocadas e discutidas em relação ao conhecido e atual efeito Sandage.

ABSTRACT. The problem of the galactic globular cluster ages is revisited, discussing the possible sources of errors and indeterminations. The role of RRLyrae variables is discussed in the frame of the evolutionary scenario. Application of a general fitting procedure to the galactic globular clusters M15 and M4 gives respectively

$t=(13\pm3)\cdot10^9$ yr and $t=(12.2\pm0.2)\cdot10^9$ yr.

A similar age for the globular cluster M3 is also suggested and discussed in relation to the problem known as Sandage's effect.

I. INTRODUCTION

The determination of galactic globular cluster age represents a very important and exciting problem in stellar astrophysics. Information on absolute ages establishes a lower limit to the age of the universe, with constraints on important cosmological quantities. On the other hand, information on the age spread suggests the timescale of the galactic halo collapse.

The distribution of cluster stars in the HR diagram is dependent on the cluster age. In particular, globular clusters have characteristic color-mag nitude diagram well interpreted in terms of the so called isochrone loci (see Figure 1).

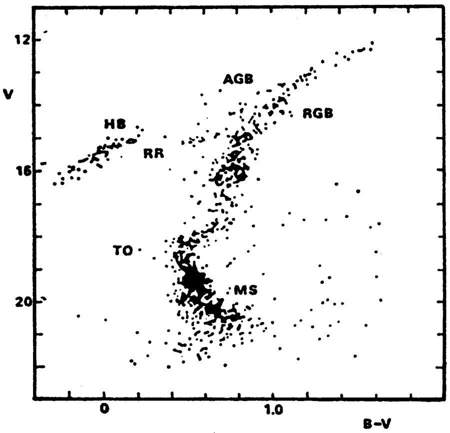

FIGURE 1. The principal morphological features for a typical globular cluster c-m diagram.

On theoretical ground, we know that the HR diagram locations of cluster main-sequence and red-giant branches do not depend, at least significantly, on the cluster age. In consequence, no information on this evolutionary parameter can be achieved by comparison of such loci with theoretical prescriptions. Horizontal branches ought to depend on the cluster age as - everything else being constant - older clusters are expected with smaller evolutionary HB masses and, in turn, hotter HB stars. However, the intervention of mass-loss prevents a theoretical age-HB color relation since we have no theoretical prescriptions about the amount of mass-loss during the red-giant branch phase. On the other hand, the region of rapid star migration off the main sequence to the giant branch, the so called turnoff region, is highly dependent on the cluster age : the older the cluster is, the lower the turnoff luminosity and temperature are. In this way, the determination of the age of a globular cluster is mainly based on the form and location of its isochrone in the region of the turnoff point. As a general rule, the cluster c-m diagram has to be compared with theoretical isochrones with the aim of reproducing the observed turnoff characteristics.

Up to date, several works have been done in order to determine the age of galactic globular clusters. Different approaches have been adopted, following two main lines : the fitting of the turnoff characteristics and the fitting of the magnitude difference between the turnoff point and HB. However, the wide range of ages for a given cluster obtained in the different works discloses how the problem is far from being settled. A significant amount of observational and theoretical uncertainties involved in these fitting processes prevents a precise determination of this evolutionary parameter. The existence of such indeterminations represents a problem to be solved in the fitting analysis used to derive globular cluster ages before obtaining any firm conclusion.

II. THE ROLE OF HB VARIABLES

The stellar evolution theories give the expected position in the HR diagram of a star with mass, age and chemical composition known. In particular, the evolutionary status of HB stars in globular clusters is, in principle, well established. If the quoted evolution theories are assumed to be reliable, for each cluster age and original chemical composition and for each assumed amount of mass-loss during the red giant stage, both the luminosity and the effective temperature of a zero-age HB star are given by the theory. In addition, the evolution theory also predicts the star evolution off ZAHB phase.

On the other hand, the occurrence of RRLyrae variables in the temperature range $3.80 \lesssim \log Te \lesssim 3.90$ provides additional and independent information on these HB structures. The fundamental period of the HB variable is a well established function of its mass(M), luminosity(L) and temperature(Te) (e.g. Iben, 1971; van Albada and Baker, 1971) :

$$\log P = 11.497 - 0.68\log M + 0.84\log L - 3.48\log Te \qquad (1)$$

where period(P) is in days and (L,M) are in solar units. For each given original chemical composition, the evolution theories correlate to each given HB mass, the luminosity and temperature. And, for each given RRLyrae variable mass, luminosity and temperature, the pulsational theory provides the expected value of the fundamental period. In this way, the independent possibilities of reproducing the observed (L,Te) and P of HB structures in galactic globular clusters can represent an important strategy for checking the evolutionary achievements and, also, for determining important evolutionary parameters of the clusters. These considerations suggest the tentative use of HB variables in the determination of the globular cluster age.

A particular pulsational approach to the globular cluster age can be taken when double-mode pulsators are observed in the clusters. This approach consists of obtaining the RRLyrae variable luminosity and so, the cluster distance modulus through the pulsational relation P-L-M-Te. From the observations, we obtain colors(Te) and fundamentalized periods. On the other hand, the pulsational theory (Cox et al, 1983; hereafter CHC) correlates the measured fundamental to first harmonic period ratio with the mass of the variable star, independent of any evolutionary calculation or assumption on original chemical composition. In this way, the HB luminosity at the variable colors can be obtained just from observational data and pulsational achievements.

III. A SELF-CONSISTENT APPROACH TO THE AGE OF THE GALACTIC GLOBULAR CLUSTERS M15 AND M3

The occurrence of double-mode RRLyrae stars in the globular clusters M15(Sandage et al, 1981; Filippenko and Simon, 1981) and M3(Goransky, 1981) suggests the use of the quoted pulsational approach to derive the age of these globular clusters.

The analysis by CHC of seven double-mode pulsators in the Oosterhoff type II cluster M15 shows that

$$M_{RR}(M15) = (0.65 \pm 0.05)\ M.$$

On the other hand, the photographic photometry of a sample of 62 M15 variables by Bingham et al(1983) provides accurate values for (B-V) colors and periods.

In order to derive the effective temperature of the variables, a reddening value for this cluster must be assumed. We adopt E(B-V)=0.08 as a best guess though a considerable range of values is suggested in the literature. The adopted value is supported by the fitting of the HR location of the variable sample(Bingham et al,1983) to the theoretical prescriptions about the edges of the instability strip(Stellingwerf,1984). Finally, from the $(B-V)_o$-Te relation by Butler et al(1978), the measured periods and the variable mass derived by CHC we can derive, through eq.(1), the luminosity of all the quoted sample of variables and then, the cluster distance modulus. The results are reported in Table 1.

TABLE 1. M15 RRLyrae mean luminosity, bolometric magnitude, visual absolute magnitude and distance modulus as a function of the assumed cluster reddening. $\overline{V(RR)}$=15.86 is assumed.

E(B-V)	$\overline{\log L}$	$\overline{Mbol}$	$\overline{Mv}$	V-Mv	$(V-Mv)_o$
0.04	1.69	0.38	0.54	15.32	15.20
0.08	1.75	0.23	0.39	15.47	15.23
0.12	1.81	0.08	0.24	15.62	15.26

Once established M15 reddening and distance modulus values, we can compare the observed c-m diagram(Sandage,1970; Sandage and Katem,1977) with appropriate theoretical isochrones(VandenBerg,1983). An original chemical composition of the order of Y=0.20 and logZ=-4 is assumed to be suitable to M15 (see Cohen,1979; Buzzoni et al,1983; Nesci,1983; Pilachowski et al,1983). Evaluations of the uncertainty caused by variations of the chemical composition values can be performed, showing that the main error in the derived cluster age is produced by the difference between the two sets of spectroscopic estimates of the cluster metallicity(Cohen's and Pilachowski's scales).

If Cohen's metallicity scale is assumed([Fe/H] =-2.2) the fitting of M15 c-m diagram to VandenBerg isochrones results in a classical age of 15 billion years (see Figure 2), where "classical age" means the age derived within a classical evolutionary frame(no rotation, solar CNO/Fe ratio, etc). The indetermination of this fitting process should be of the order of ±3 billion years, where the quoted fitting process is based just on the reproduction of the observed turnoff luminosity.

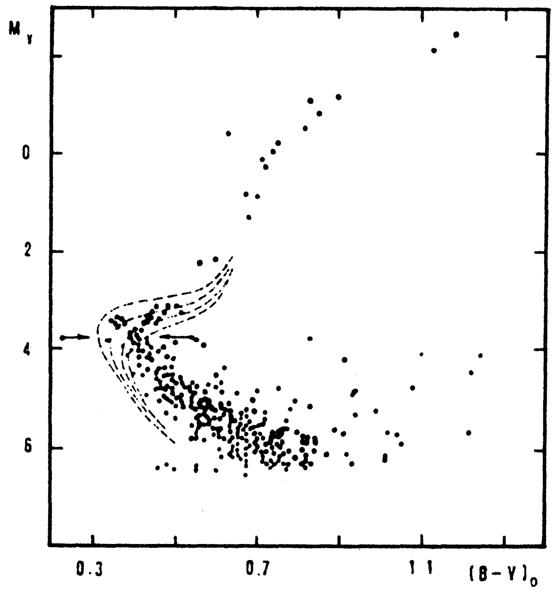

FIGURE 2. The HR diagram location of faint stars in M15 compared with VandenBerg isochrones for Y=0.20, logZ=-4 and for the adopted reddening E(B-V)=0.08 mag. The arrows indicate the assumed location of the observed turnoff(Caputo et al,1984).

However, we note that the masses of ZAHB stars at the instability strip for a cluster of metallicity logZ=-4 are - within the adopted classical scenario - as large as 0.75-0.80 $M_\odot$, i.e., 0.1 $M_\odot$ larger than the value derived by CHC. Since pulsational achievements are firmly reliable, it would seem that the classical theoretical frame is no more compatible with the actual evolutionary situation. In particular, from current evolution theories a self-consistent approach to this problem can be achieved when

$$\Delta Mc = 0.012\ M_\odot \quad \text{and} \quad [CNO/Fe] = 1.1$$

where ΔMc is the enhancement of the classical helium-core mass size and [CNO/Fe] =log(CNO/Fe)-log(CNO/Fe)$_\odot$. When the solar CNO/Fe ratio is released, the previously estimated M15 age has to be changed, being our final best value for the cluster age :

$$t(M15) = (13\pm3)\cdot 10^9 yr$$

with a maximum error (helium content, reddening, RRLyrae mass uncertainties) no larger than 1 billion years. Assuming Pilachowski's metallicity scale rather than Cohen's one would decrease the derived age to about 12 billion years (for details see Caputo et al,1984).

Following their analysis, CHC in a brief discussion of the Oosterhoff type I cluster M3 suggested a probable RRLyrae variable mass of (0.55±0.05) $M_\odot$ for this cluster. If the quoted mass value is taken as representative of M3 HB pulsators then, following the previously discussed procedure, one would derive the classical age (Caputo et al,1985a) :

$$t(M3) = (16\pm3)\cdot 10^9 yr.$$

However, the classical evolutionary frame should also be neglected in the case of M3 since the classical evolutionary variable masses are again 0.1 larger than the mass value suggested in th CHC analysis. It is necessary to consider

$$\Delta Mc = 0.0 \qquad \text{and} \qquad [CNO/Fe] = 0.92$$

in order to get a self-consistent approach to the suggested cluster data. Finally, the best value fcr M3 age should be (Caputo et al,1985a) :

$$t(M3) = (14\pm3)\cdot 10^9 \text{ yr}.$$

At this point, it is important to note that the reliability of this derived age depends on further confirmation of the adopted HB variable mass as only two stars have been analysed by CHC. In any case, it is worth to notice that the above results seem to suggest that the classical ZAHB evolutionary models coupled with a small amount of non canonical variation of the helium-core mass represent a probable way to explain the observed period difference between M15 and M3 variables and and are likely to offer an explanation of the Sandage's effect (at least regarding these two clusters).

IV. REDDENING, DISTANCE MODULUS AND AGE OF THE GLOBULAR CLUSTER NGC 6121 (M4) FROM THE PROPERTIES OF RRLYRAE VARIABLES.

Richer and Fahlman(1984) (hereafter, RF) performed CCD photometry of the galactic globular cluster M4 obtaining an accurate c-m diagram for the main-sequence stars. In this work, the cluster reddening and distance modulus were estimated and the comparison of VandenBerg appropriate isochrones to the observed main-sequence provided an estimate for the cluster age of

$$t(M4) = (15\pm1)\cdot 10^9 \text{ yr}$$

being Y=0.20 and Z=2(-3) the original chemical composition adopted for this cluster.

We note that the full consistency of the cluster parameters involved in the quoted fitting process and of the derived cluster age can be investigated also through a pulsational approach.

By taking into account the reddening and distance modulus derived by RF, we can locate the sample of observed RRLyrae variables(Cacciari,1979; Sturch,1977) in the HR diagram and then, we can investigate the agreement with the theoretical prescriptions about the HR location of the instability strip (Stellingwerf,1984). This comparison is shown in Figure 3.

On the other hand, by assuming an appropriate value for the RRLyrae variable mass and by converting the observed visual magnitudes and colors of the variables into the theoretical plane (L,Te), we can construct theoretical period-frequency histograms. The resulting histograms have to be compared with the observed one(Sawyer-Hogg,1973). Figure 4 shows this comparison for three assumed variable mass values.

In order to achieve a full agreement between theory and observations the adopted reddening and distance modulus have to be changed, producing variations of the classical age of M4 derived by RF. The resulting variations are shown in Table 2.

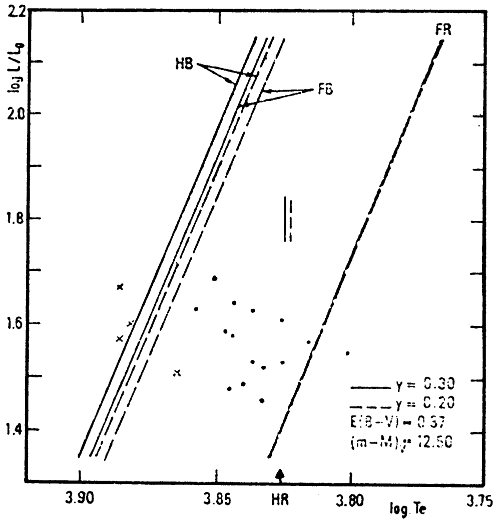

FIGURE 3. The location of the c-type(crosses) and ab-type RRLyrae variables in M4 for the labelled values of redden- ing and distance modulus (RF). The blue edges for first har- monic(HB) and fundamental(FB) pulsators, as well as, the red edge of the instability strip (FR) are shown for two assump- tions on the external helium. On the abcissa, HR indicates the temperature of transition between c and ab-type varia- bles (Caputo et al,1985b).

FIGURE 4. Period-frequency histogram for M4 RRLyrae variables:
a) the observed values
b,c,d) the theoretical values for the three la- belled variable masses (Caputo et al,1985b).

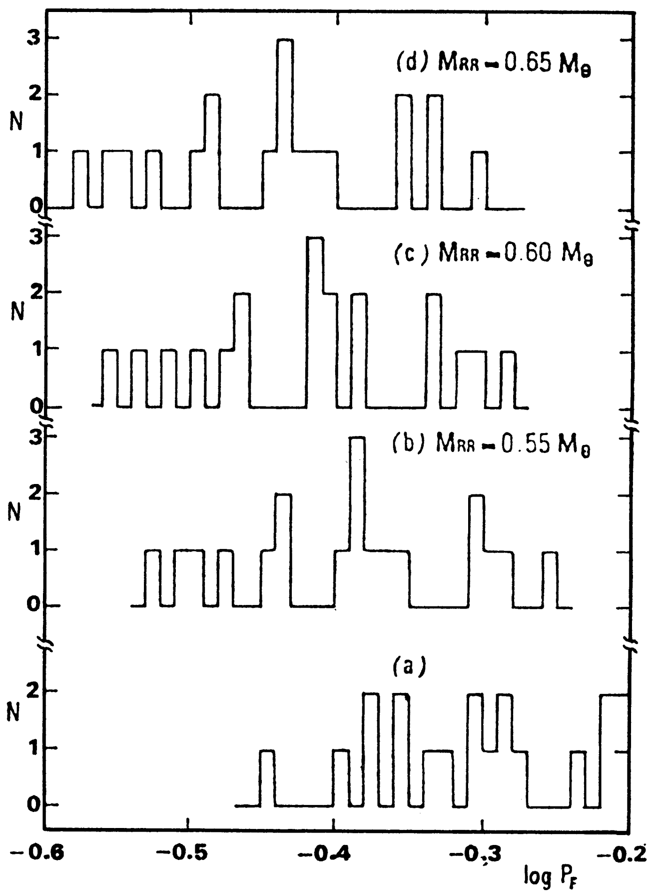

TABLE 2. Variations of the reddening and distance modulus of M4 adopted by RF for the three assumed variable masses. The resulting variations of the RF classical age ($t=15\cdot10^9$ yr) are given in the last column.

$M(M_\odot)$	$\Delta(V-M_V)$	$\Delta E(B-V)$	$\Delta t(10^9)$
0.55	0.11	-0.04	-1.4
0.60	0.17	-0.05	-2.2
0.65	0.21	-0.05	-2.7

A self-consistent approach to M4 age requires also the agreement between the evolution theory and the cluster variable data (mass and luminosity). The non classical variations of the solar ratio CNO/Fe and of the evolutionary helium-core mass size necessary to get the quoted agreement are reported in Table 3 together with the resulting M4 ages.

TABLE 3. For each given variable mass, the required non-classical variations are given. In the fourth column, the decrease of the age due to the CNO/Fe variation is given. In the last column, the net result is reported as the coupling of t given in the last column of Table 2 and the fourth column in the present one.

$M(M_\odot)$	[CNO/Fe]	ΔM_c	$\Delta t(10^9)$	$t(10^9)$
0.55	0.70	0.005	-1.4	12.2
0.60	0.40	0.010	-0.8	12.0
0.65	0.00	0.013	0.0	12.3

As a result, we derive the cluster age

$$t(M4) = (12.2\pm0.2)\cdot10^9\,\text{yr}$$

where the labelled error represents the indetermination in the RRLyrae variable mass and, consequently, the indeterminations in the cluster reddening and distance modulus. It is worth emphasizing that a total uncertainty of ±2 billion years would take into account also indeterminations in metallicity and helium content. For a more detailed discussion see Caputo et al (1985b).

V. FINAL REMARKS

The present results seem to strengthen earlier suggestions of a constant age for the galactic globular cluster system, independing on the cluster metallicity. The present determination of M15, M3 and M4 ages are based on a self-consistent theoretical solution which holds as long as present available theoretical models are reliable. Further clusters should be analysed in order to confirm the present results and suggestions.

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