47 TUC: THE SPECTROSCOPIC VERSUS CMD AGE DISCREPANCY

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ABSTRACT

We investigate current problems in obtaining reliable ages for old stellar systems based on stellar population synthesis modelling of their integrated spectra. In particular, we address the large ages derived for the globular cluster 47 Tuc, which is at odds with its Color-Magnitude-Diagram (CMD) age. Using a new age indicator, Hγ<130, which is particularly effective at breaking the degeneracy between age and metallicity, we confirm the discrepancy between the spectroscopic age and the CMD age of 47 Tuc, in that the spectroscopic age is much older. Nebular emission appears unlikely to be a source for weakening the observed Balmer lines. We then explore a number of key parameters affecting the temperature of Turn-Off stars, which are the main contributors to the Balmer lines for old metal-rich stellar populations. We find that α-enhanced isochrones with atomic diffusion included not only provides a good fit to the CMD of 47 Tuc, but also leads to a spectroscopic age in better agreement with the CMD age.

Subject headings: galaxies: evolution — galaxies: stellar content — Galaxy: globular clusters: general — Galaxy: globular clusters: individual (47 Tuc) — stars: evolution

1. INTRODUCTION

An estimate of the mean luminosity-weighted stellar age of an early-type galaxy represents a major step in unveiling its true star formation history. However, to derive reliable information about stellar ages from the integrated light of unresolved galaxies one must deal with the age-metallicity degeneracy problem, which affects not only integrated colours but also absorption line-strengths (Worthey 1994). Recently, new age-dating techniques based on the Balmer lines (e.g., Jones & Worthey 1995; Vazdekis & Arimoto 1999, thereafter VA99) have shown great promise in untangling the age-metallicity degeneracy. These techniques should be tested and calibrated on the metal-rich Galactic globular clusters (GCs) for which, unlike elliptical galaxies, independent age estimates are possible (Gibson et al. 1999, thereafter G99) by means of the Color-Magnitude-Diagram (CMD) of their resolved stellar population.

The application of the new age-dating techniques to very high signal-to-noise ratio (S/N) spectra of metal-rich Galactic GCs has revealed two major concerns: i) the obtained ages are unreasonably large (>20 Gyr) (Jones 1999; Cohen, Blakeslee & Ryzhov 1998; G99; VA99) and ii) a severe disagreement is found between the spectroscopic and CMD ages of 47 Tuc (G99). The CMD-derived ages may be sensitive to the dating method employed (e.g., Alonso et al. 1997) and to the input physics of the theoretical isochrones used as a reference (e.g., Salaris & Weiss 1998, thereafter SW98). However, a variety of recent CMD-based age determinations for 47 Tuc have consistently found its age to lie within 9-12.5 Gyr (SW98; Gratton et al. 1997; Carretta et al. 2000; Liu & Chaboyer 2000).

These CMD-derived ages are substantially younger than the >20 Gyr spectroscopically derived age obtained by G99 using the age indicator of Jones & Worthey (1995), and Worthey (1994) stellar population models. This discrepancy shows clearly that current stellar population synthesis models used for interpreting the integrated light of stellar systems may have severe zero points problems.

In § 2 we improve the spectroscopic age-dating technique which confirms a large spectroscopic age for 47 Tuc. In § 3 we discuss the possible origin of the problem, explore several theoretical parameters and suggest a possible solution. Finally, in § 4 we present our conclusions.

2. A NEW Hγ AGE INDICATOR: 47 TUC AGE ESTIMATE

In this study we make use of the evolutionary stellar population synthesis model of Vazdekis (1999) (hereafter V99), which predicts spectral energy distributions in the optical wavelength range for single burst old-aged stellar populations of metallicities (−0.7 ≤ log(Z/Z⊙) ≤ +0.2), at resolution 1.8Å (FWHM). This approach is different from the one followed by previous models (e.g., Worthey 1994; Vazdekis et al. 1996) which used mostly the Lick/IDS polynomial fitting functions (Worthey et al. 1994; Worthey & Ottaviani 1997) to relate the strengths of selected absorption features to stellar atmospheric parameters. These fitting functions are based on the Lick/IDS...
stellar library (FWHM~9 Å, Worthey et al. 1994), thus limiting the sensitivity of the models to weak features. However V99 model provides full SEDs rather than predicted index strengths and therefore the Lick indices defined in Worthey et al. (1994) and Worthey & Ottaviani (1997) as well as those of Rose (1994) and Jones & Worthey (1995) are measured directly on the SEDs of V99 models (without the use of any fitting functions). This approach makes it easy to define new indices and even to confront the model predictions to the detailed structure of observed absorption features. V99 models have been recently updated (Vázquez 2000, in preparation) with Girardi et al. (2000) scaled-solar isochrones and new empirical photometric libraries, such as Alonso et al. (1999).

The chief impediment to obtaining reliable ages of elliptical galaxies is caused by the degenerate effects of age and metallicity on the integrated spectra of old stellar populations (e.g., Worthey 1994). Recently, VA99 have proposed a new age indicator, centered on Hγ, which provides unprecedented power for breaking the age-metallicity degeneracy. Their index is a pseudoequivalent width measurement, relying on the pseudocontinuum peaks immediately longward and shortward of Hγ, and is an improvement over earlier pseudoequivalent width Hγ indices (Rose 1994; Jones & Worthey 1995) in being relatively insensitive to spectral resolution. We have redefined the VA99 index, to take full advantage of the information available in an integrated spectrum with σ ∼ 100 km s⁻¹ and to make the index as insensitive as possible to metallicity. This new index, Hγσ<130, is composed of two pseudocontinua, λλ 4329.000-4340.468Å and 4352.500-4368.250Å, and the feature at λλ 4333.250-4363.000Å. The main difference with respect to the VA99 definition is that the feature now also covers the neighboring metallic line centered on λ ∼ 4352Å. The two pseudocontinua severely overlap the index passband aiming at making Hγσ<130 stable against changes in the spectral resolution (see below), and insensitive to metallicity variations on the basis of the compensating effect raised up by VA99: at a given age, Hγ strengthens with metallicity owing to the adjacent metallic absorption, but on the other hand the pseudocontinua are depressed by the effects of the neighboring FeI lines on both sides of Hγ (see VA99 for an extensive explanation).

Fig. 1 shows the age disentangling power of the Hγσ<130. In the left panel, the indices for both M 32 (Jones 1999 spectrum) and for 47 Tuc (Rose 1994 spectrum) are plotted relative to the models. The age estimate for M 32 is consistent with VA99 result (∼4 Gyr), based on the earlier Hγ index. The principal issue for this paper, however, is the very large age inferred for 47 Tuc, i.e., well in excess of 15 Gyr. This disturbingly large inferred age confirms that already obtained by G99 and VA99, and thus is a feature of all recent studies of this cluster (based on different observational spectra). The right panel of Fig. 1 shows the insensitivity of Hγσ<130 to resolution in the range 60 < σ < 130 km s⁻¹. Spectra of S/N(Å)~175 and a very careful correction of any λ shift (see VA99), are required to take the full advantage of this index.

Fig. 2 further illustrates the age-metallicity resolving power achieved with the Hγσ<130 index, and further clarifies the troublesome problem of the inferred age for 47 Tuc. Here, Hγσ<130 is plotted versus several different indices defined in Worthey et al. (1994) and Rose (1994). All the indices were measured directly on the model SEDs of V99 smoothed to match the resolution of the spectrum of 47 Tuc. Again, all index plots indicate an age for 47 Tuc in excess of 15 Gyr. In addition, most of the plots in Fig. 2 suggest a metallicity for the cluster around 0.1-0.2 dex lower than the Carretta & Gratton (1997) value of [Fe/H]=-0.7, which is based on high dispersion spectra of individual red giants. On the other hand, Gratton & Sneden (1991) and Brown & Wallerstein (1992), obtained [Fe/H]~−0.8 and −0.9, respectively. Recently, Liu & Chaboyer (2000) obtained [Fe/H]=−0.95 using the isochrone fitting technique. However, it bears emphasizing that the uncertainty in metallicity does not affect the age discrepancy shown here.

3. Discussion

In this section we explore possible causes for the 47 Tuc age discrepancy: emission line contamination, possible peculiarity of the cluster, horizontal branch contribution, mixing length calibration, α-elements enhancement, initial helium abundance and atomic diffusion.

3.1. Nebular emission

G99 pointed out that gas emission could be partially filling in Hγ. We therefore studied other Balmer lines, since emission would affect them by differing amounts, according to standard Case B recombination line physics (e.g., Osterbrock 1989). Fig. 3 shows that the derived age for 47 Tuc is essentially independent of the Balmer line used. If emission fill-in were the cause of the large spectroscopic
age, one would expect the ages derived from Hβ and Hδ to be older and younger, respectively, than that obtained from Hγ. To quantify this statement, we have used a flux-calibrated spectrum of the Orion Nebula as a template for adjusting the Balmer line intensities to exactly match the calibrated spectrum of the Orion Nebula as a template for from Hγ to be older and younger, respectively, than that obtained from the 47 Tuc spectrum adjusted the Balmer line intensities to exactly match the calibrated spectrum of the Orion Nebula as a template for the numbers (Gyr).

Fig. 2.— $H_{\gamma}^{\sigma<130}$ Versus different indices as defined in Worthey et al. (1994) (Ca4227; Fe4383) and Rose (1994). All these indices were measured on the two, the 47 Tuc spectrum of Rose (1994), and V99 models smoothed to $\sigma=100$ km s$^{-1}$. Line types as in Fig. 1, while thin dotted lines mean models of equal ages indicated by the ages from different Balmer lines are, in fact, discordant, although the degree of discrepancy is probably not sufficient to eliminate the emission hypothesis altogether.

An additional problem for the emission hypothesis comes from the fact that spectra of other metal-rich Galactic globular clusters exhibit the same “anomalous” behavior in Hγ as 47 Tuc. Specifically, in Rose (1994) a spectrum formed from the composite of four metal-rich globulars (NGC6356, NGC6624, M69, and M71) is compared to that of 47 Tuc (and M32), and shown to be nearly indistinguishable with 47 Tuc in all respects, including the pseudoequivalent width index for Hγ. We have further quantified this fact by measuring the $H_{\gamma}^{\sigma<130}$ indices for the four clusters. On average, $H_{\gamma}^{\sigma<130}$ for the four clusters is 0.87, i.e., slightly lower even than for 47 Tuc. Thus if the emission hypothesis is correct, then in composite, the other four clusters must have essentially the same amount of emission fill-in as 47 Tuc. Such a scenario appears to be rather contrived. In short, emission fill-in appears to be an unlikely source of the weak Balmer lines in 47 Tuc, but a more definitive assessment of the emission hypothesis could be achieved via deep interference filter imaging of the cluster.

In mentioning the other four metal-rich globular clusters it is also worth noting that there are still some integrated light properties of metal-rich clusters (e.g., anti-correlation between strengths of CN bands and the SrII4077 line) that remain unexplained, both among Galactic (Rose &

3.2. Is 47 Tuc a peculiar cluster?

A second possibility is that 47 Tuc is peculiar among Galactic GC’s. However, by sketching the models of Vazdekis et al. (1996) to the Mg$_2$-Hβ plot of Burstein et al. (1984) (c.f. their Fig. 5k) we see that a number of metal-rich Milky Way GC’s fall well below the model lines (e.g., models of [Fe/H]=−0.7 and 16 Gyr yield Mg$_2$~0.17 and Hβ~1.7). The same result is achieved if Worthey (1994) model grids are used. VA99, Vazdekis et al. (1996; c.f., their Fig. 8), and Cohen, Blakeslee & Ryzhov (1998) find analogous results for a set of metal-rich galactic GC’s. Finally, as mentioned above the composite spectrum of four metal-rich clusters analyzed in Rose (1994) is similar in all respects to 47 Tuc.

3.3. The Horizontal Branch contribution

The Balmer indices are dominated by the hottest stars along the isochrone (e.g., Rose 1994; Worthey 1994; Buzzoni, Mantegazza & Gariboldi 1994), i.e., by TO and Horizontal Branch (HB) stars. For a GC with a red HB such as 47 Tuc we have verified that the contribution due to HB stars is negligible for this index. In fact, a decrease of the HB stars temperature by 150 K yields $H_{\gamma}^{\sigma<130}$ values smaller by less than 0.01 A, in the range of ages 6-16 Gyr. Therefore, the discrepancy between the integrated light and CMD ages must be found in the TO. On the basis of Fig. 1 and the TO temperatures of our isochrones we estimate that to decrease $H_{\gamma}^{\sigma<130}$ by $\sim 0.050$ A (to match the observed value for typical CMD ages) requires a TO cooler by $\sim 200$ K, for a given age. We therefore should look at those parameters affecting the TO effective temperature.

3.4. Mixing length

The stellar models we use adopt a solar calibrated value of the mixing length. This assumption is in agreement with results from current 2-D hydrodynamical simulation of superadiabatic stellar convection, even for non solar metallicity stars (Freytag & Salaris 1999). However, we have also tested an alternative prescription for the treatment of superadiabatic convection in stellar envelopes, namely, the Full Spectrum Turbulence theory (FST – see,
e.g., D’Antona, Caloi & Mazzitelli 1997). We find that for the age and metallicity regime typical of 47 Tuc the difference of TO effective temperatures between solar calibrated mixing length and FST models are negligible (~10 K).

3.5. \(\alpha\)-elements enhancement

The chemical composition of 47 Tuc stars (and of Galactic GCs in general) is enhanced in \(\alpha\) elements (we mean mainly O, Ne, Mg, Si, S, Ca, Ti – see, e.g., the review by Carney 1996). Spectroscopic determinations of \(\alpha\) elements abundances in 47 Tuc stars have been performed by Gratton et al. (1986), Brown et al. (1990), Brown & Wallerstein (1992), Norris & Da Costa (1995): their results, as summarized by Carney (1996), provide \(<[O/Fe]> = 0.53 \pm 0.08\) and an average enhancement of \([\text{Si+Ca+Ti}/\text{Fe}]\) of about 0.20 dex.

Moreover, as demonstrated by SW98 and confirmed by VandenBerg, Swenson & Alexander (2000), for the \([\alpha/\text{Fe}]\) ratios observed in Galactic GCs \(([\alpha/\text{Fe}]=0.3 - 0.4)\) and \([\text{Fe/H}] > 1\), it is not valid to use scaled-solar isochrones with the same global metallicity as the \(\alpha\)-enhanced ones to approximate the effect of the \(\alpha\)-elements enhancement. As a preliminary test we computed selected scaled-solar isochrones using the same code and input physics as in SW98, providing a good agreement for the TO temperatures using the same code and input physics as in SW98, with the corresponding isochrones of Girardi et al. (2000) isochrones). The referee asked our empirical prescriptions (the same ones that we applied SW98, transformed to the observational plane following Lebreton et al 1996). Lebreton et al. (1999) showed that diffusion of the \(H_\gamma\) feature at \(\lambda\) 4340Å due to a higher metallicity (caused by the lower temperatures of TO stars due to higher opacity of the stellar matter) is compensated by a deepening of the adjacent iron lines (mainly at the blue side of \(H_\gamma\)). The \(H_\gamma_{<\lambda<130}\) index definition takes into account this effect, and thus is insensitive to metallicity variations. Using the \(\alpha\)-enhanced isochrones at a given \([\text{Fe/H}]\) the global metallicity is higher and therefore the temperatures of the stars slightly lower, causing a weakening of the \(H_\gamma\) feature which is not compensated by any deepening of the adjacent iron lines. Therefore, this effect is very similar to the one produced by an age increase. Furthermore, we also have tested \(\alpha\)-enhanced isochrones with \([\text{Fe/H}] = 0.3\) \((Z=0.02)\), confirming that for a given \(\alpha\)-enhancement the \(H_\gamma_{<\lambda<130}\) index preserved its age resolving power.

3.6. Primordial helium content

We find that a reasonable variation of the initial He content does not appreciably affect the spectroscopic age. In Fig. 4 the \(H_\gamma_{<\lambda<130}\) values obtained on the basis of \(\alpha\)-enhanced isochrones with a solar initial He abundance \((Y=0.273)\) are not significantly different from the ones computed with \(Y=0.254\) at the 47 Tuc metallicity \((\Delta Y/\Delta Z=3)\).

3.7. Atomic diffusion

Atomic diffusion is capable of changing the TO temperature of low mass stars at a given age (see, e.g., Profitt & Vandenberg 1991, Chaboyer et al 1992, Castellani et al 1997, Cassisi et al 1998, Salaris, Groenewegen & Weiss 2000). The occurrence of this physical process in the sun has been demonstrated by helioseismic studies (e.g., Guenther et al 1996). Lebreton et al. (1999) showed that diffusion is required to reproduce the temperatures of Hippar-
cos subdwarfs with $-1.0 < [\text{Fe/H}] < -0.3$. Due to diffusion, the surface metallicity and He content decrease during the Main Sequence phase (MS) due to their sinking below the convective envelope. Around the TO the surface [Fe/H] and Y show a minimum; then evolutionary timescales become much shorter and diffusion is no longer effective. Moreover, since envelope convection deepens, almost all metals and He diffused toward the center are engulfed again in the convective envelope. Along the Red Giant Branch the surface [Fe/H] (and He) is restored to nearly its initial value (the current spectroscopic determinations of [Fe/H] for GCs make use of Red Giant stars, so that the measured metal abundances truly reflect the initial ones). For a given initial chemical composition and age, TO temperatures are significantly cooler than in isochrones without diffusion (the TO luminosities are reduced too, thus causing an age reduction by $\gtrsim 1$ Gyr if the TO brightness is used as age indicator). The reason for this behavior is that the inward settling of He during the MS raises the core molecular weight and the molecular weight gradient between surface and center of the star. This increases the stellar radius and the rate of energy generation in the center. The diffusion of the metals partially counterbalances this effect by decreasing the opacity in the envelope and increasing the central CNO abundance.

We have calculated a new set of isochrones (initial metallicity $[\text{Fe/H}]=-0.7$) with He and metals diffusion included as in Salaris et al. (2000), and using the same input physics and [\text{Fe/H}] for GCs make use of Red Giant stars, so that the measured metal abundances truly reflect the initial ones). For a given initial chemical composition and age, TO temperatures are significantly cooler than in isochrones without diffusion (the TO luminosities are reduced too, thus causing an age reduction by $\gtrsim 1$ Gyr if the TO brightness is used as age indicator). The reason for this behavior is that the inward settling of He during the MS raises the core molecular weight and the molecular weight gradient between surface and center of the star. This increases the stellar radius and the rate of energy generation in the center. The diffusion of the metals partially counterbalances this effect by decreasing the opacity in the envelope and increasing the central CNO abundance.

We have calculated a new set of isochrones (initial metallicity $[\text{Fe/H}]=-0.7$) with He and metals diffusion included as in Salaris et al. (2000), and using the same input physics and $\alpha$-enhancement as in SW98. Fig. 2 shows the fit to the 47 Tuc CMD of both Kaluzny et al. (1998) and Hesser et al. (1987) using these isochrones. The derived age (determined from the TO luminosity once the distance is fixed) is 9-11 Gyr. We obtain similar results when fitting the V-I versus V diagram using data of Kaluzny et al. (1998), with the exception that a better fit is attained for the giant branch than in the B-V versus V diagram. Fig. 3 shows the $H_{\alpha}<130$ measurement for the model spectra computed on the basis of these new isochrones; the CMD age as estimated from Fig. 3 is still smaller by $\sim 2$ Gyr than the minimum age allowed by the $H_{\alpha}<130$ measurement, but much more consistent with the $H_{\gamma}$ age derived employing the same set of isochrones than obtained before. The right panels of Fig. 3 show that use of these new models does not significantly change our metallicity estimate for the cluster.

4. CONCLUSIONS

We have discussed the origin of the discrepancy between the spectroscopic (based on the effective temperature of TO stars) and CMD (based on the luminosity of TO stars and an assumed distance scale) age estimate for 47 Tuc as raised by G99. For this purpose we have defined a new age indicator, $H_{\gamma}<130$, particularly suitable for studying GCs and low velocity dispersion galaxies, which shows a superb power to break the age-metallicity degeneracy. $H_{\gamma}<130$ confirms the age discrepancy found by G99 for 47 Tuc. Emission fill-in of the Balmer lines appears to be an unlikely source of the weak $H_{\gamma}$ in 47 Tuc, since the ages derived from different Balmer lines give discordant results if the hypothetical emission fill-in is corrected for, and since a composite of four other metal-rich Galactic globular clusters shows the same weak $H_{\gamma}$ phenomenon. Thus the fact that other metal-rich GCs show very similar low Balmer values in comparison to the model predictions suggests a problem in the zero point of current stellar population models. It is worth noting that this zero point problem of the models with respect to the metal-rich GCs also works out for old elliptical galaxies.

We therefore analyzed the possible causes of the problem by studying a number of input parameters of the evolutionary computations, and comparing the observed value of $H_{\gamma}<130$ with that derived from the synthesized integrated spectra. Neither the initial He content nor the HB have significant effects on the Balmer indices synthesized for 47 Tuc. However the inclusion of $\alpha$-element enhancement and atomic diffusion in the evolutionary models provide spectroscopic ages which are much closer to the CMD derived ages. This occurrence constitutes a possible solution to the age-discrepancy between CMD and integrated spectrum ages of old metal-rich stellar populations.

It is important to study if the age discrepancy is present in metal poor GCs. For this purpose we need to expand the current stellar spectral libraries which feed the stellar population models (see V99), to extend their predictions to lower metallicities.

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Fig. 5.— In the left we plot the CMD of 47 Tuc (data of Kaluzny et al. 1998 plotted as small circles; that of Hesser et al. 1987 plotted as large circles). Overplotted are various isochrones of $[\text{Fe/H}]=-0.7$, $[\alpha/\text{Fe}]=+0.4$, $Z=0.008$ and atomic diffusion for different ages. In the right we plot the V-I versus V diagram using data of Kaluzny et al. (1998).