THE SPECTROSCOPIC AGE OF 47 TUCANAE

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ABSTRACT

High signal-to-noise ratio integrated spectra of the metal-rich globular cluster 47 Tuc, spanning the HγHR and Fe 4668 line indices, have been obtained. Jones & Worthey have suggested that the combination of these indices is the best available mechanism for cleanly separating the age-metallicity degeneracy that hampers the dating of distant, unresolved, elliptical galaxies. For the first time, we apply this technique to a nearby spheroidal system, 47 Tuc, for which independent ages, based upon more established methods, exist. Such an independent test of the technique’s suitability has not been attempted before but is essential before the technique’s application to more distant, unresolved, stellar populations can be considered valid. Because of its weak series of Balmer lines relative to model spectra, our results imply a spectroscopic age of 47 Tuc well in excess of 20 Gyr, which is at odds with the color-magnitude diagram age of 14 ± 1 Gyr. The derived metal abundance, however, is consistent with the known value. Although the observational constraints are restrictive, existing data cannot entirely exclude emission “fill-in” of the Hγ line as the source of the discrepancy.

Key words: galaxies: abundances — galaxies: elliptical and lenticular, cD — globular clusters: individual (47 Tucanae) — stars: abundances

1. INTRODUCTION

The star formation history of elliptical galaxies still remains, at many levels, a mystery. The fundamental uncertainty that afflicts attempts to determine the ages of such (presumably) old stellar populations lies in the unfortunate fact that age and metallicity have almost identical effects on broadband colors and on most line indices (O’Connell 1976). This age-metallicity degeneracy—sometimes referred to as the 3/2 rule (Worthey 1994)—has led many (e.g., O’Connell 1976; Worthey 1994; Rose 1994) to search for individual absorption features that may be sensitive to either age or metallicity, but not both.

Unfortunately, line indices have not proved to be the panacea once hoped for. As Worthy (1994, see his Table 6) has shown, the vast majority of low-resolution lines defined by the Lick/IDS survey (e.g., Worthey et al. 1994) lie uncomfortably close to the 3/2-rule degeneracy “zone.” An encouraging result to come out of the Worthy (1994) IDS study, however, was the identification of one particularly useful—and strong—indicator apparently free of any strong age influence. Fe 4668, whose bandpass spans ~4635–4722 Å, not only tracks Fe but also contains a strong contribution from C2, Ti, Cr, and Mg, and, as Worthy, Trager, & Faber (1995) note, is currently the best candidate tracer for the mean metallicity “Z,” being almost exclusively sensitive to it.

On the other hand, identifying a matching “pure” age discriminator has proved to be more difficult. Hα and Hβ have long been popular indices in this regard (e.g., O’Connell 1976), but, as stressed by González (1993), both lines can be easily distorted (even filled in) by emission from ionized gas, severely compromising their usage. Higher order Balmer emission lines (e.g., Hδ and Hγ) are admitted weakly weaker; yet, they are free of such emission complications and appear to provide a very sensitive age diagnostic. Rose (1994) recognized this latter fact and designed a set of higher resolution line indices in order to take advantage of these age-discriminating “powers.” The Rose system employs a 3.74 Å window, over which the line indices are measured; in contrast, the Lick/IDS system (typically) uses a ~40 Å window. One index in particular, HγHR—Ca iHR age-metallicity diagnostic diagram.

Jones & Worthy (1995) stress several caveats regarding their proposed optimal age-dating technique. First, while the parameter-space coverage (e.g., Teff, log g, and [Fe/H]) of their stellar library, upon which the model sequences are ultimately based, is good, it is not complete. Specifically, there is an admitted lack of metal-poor stars, especially hot, horizontal-branch stars, which could contribute to the Balmer line absorption. Because of this, Jones & Worthy (1995) emphasize that their sequences are not directly applicable to systems with metallicities outside −1.0 ≤ [Fe/H] ≤ +0.6. Second, in order to apply this technique accurately to integrated spectra of spheroidal systems, very high signal-to-noise ratios (≥ 100) at moderately high spectral resolutions (~ 1 Å) are a necessity.

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5 The “HR” subscript stands for high resolution, in order to distinguish the Rose-style equivalent widths, with 3.74 Å bandpasses, from the Lick-style indices, which are an order of magnitude broader.
To this end, Jones & Worthey (1995) present such a spectrum for M32 and find an age of $\sim 6$–7 Gyr, which is in agreement with O’Connell (1980) and Rose (1994). While this result is a necessary proof of the technique, it is not a sufficient one, as it effectively compares two population synthesis methods, each of which indirectly determines an age estimate. Optimally, any testing of a new—and potentially exciting—technique should be completely independent at some level. Unfortunately, there are simply no independent estimates. Optimally, any testing of a new and potentially exciting technique should be completely independent at some level. Fortunately, there are simply no independent estimates. Optimally, any testing of a new and potentially exciting technique should be completely independent at some level. Unfortunately, there are simply no independent estimates. Optimally, any testing of a new and potentially exciting technique should be completely independent at some level.

Indirectly, using the Milky Way, with its metal-rich globular clusters. Metal-rich globular clusters are the only practical systems with which to independently assess the reliability of the H$_{\text{IR}}$–Fe 4668 age-dating technique. This is true because accurate ages have already been determined for at least four clusters in the metal-rich regime to which the Jones & Worthey technique is applicable (e.g., Richer et al. 1996). With its high metallicity (i.e., [Fe/H] $\approx -0.7$) and color-magnitude diagram (CMD) derived age of 14 $\pm$ 1 Gyr (Richer et al. 1996), the southern globular cluster 47 Tuc is an ideal laboratory within which to test this new age-dating technique.

Observations of existing high-resolution integrated spectra of 47 Tuc in the literature include those of Smith (1979) and Rose (1994). In both cases, though, the observations were restricted to $\lambda < 4400$ Å, meaning the metallicity-discriminant Fe 4668 line index could not be measured.

In §2, we briefly describe our new observations of 47 Tuc, which now provide simultaneous coverage of both the age-sensitive feature H$_{\text{IR}}$ and the metallicity-sensitive features Ca$_{\text{IR}}$ and Fe 4668. Such data will allow us to test how accurately the spectroscopic age of this simple stellar population agrees with its accurately determined CMD age. The results of our analysis are discussed in §3 and summarized in §4.

2. OBSERVATIONS AND ANALYSIS

Two high signal-to-noise ratio (S/N $\geq 100$) integrated spectra of 47 Tuc were acquired during the nights of 1996 October 20 and 21, using the coude spectrograph with the 32 inch (81 cm) Schmidt camera (grating E; first order) on the 74 inch (1.9 m) telescope at Mount Stromlo Observatory. The 1:1 slit was scanned back and forth (east-west) to limits of $\pm 0.55$ from the cluster center (total coverage in excess of 2.5 core radii, ensuring that stochastic fluctuations due to finite sampling were minimized) for $\sim 30$ minutes per exposure. The 24 $\mu$m pixels of the Tek 2K $\times$ 2K CCD translated to 0.48 Å pixel$^{-1}$—i.e., 983 Å of spectral coverage, which, for a central wavelength setting of 4500 Å, allowed simultaneous determination of Ca$_{\text{IR}}$, H$_{\text{IR}}$, and Fe 4668 indices. Companion blank-sky exposures (again, of $\sim 30$ minutes’ duration, taken $\sim 20'$ to the north of the cluster center) were acquired subsequent to each 47 Tuc exposure. The relative strength of the sky versus cluster signal was negligible. For calibration purposes, 13 stars (spanning a range of metallicity and spectral type) in common with Jones’s coude feed spectral library (see §2.4 of Leitherer et al. 1996; Jones 1996b) and the Lick/IDS library (Worthey et al. 1994) were observed, as were two spectrophotometric standards. Standard IRAF tasks were employed for the flat-fielding and flux and wavelength calibrations. Observations taken throughout the run of bright, metal-poor halo giants imply that sky subtraction has not introduced any unforeseen spectral artifacts. Because the central, one-dimensional velocity dispersion of 47 Tuc is only $\sigma_v = 11.6 \pm 1.4$ km s$^{-1}$ (Meylan & Mayor 1986), no correction for internal dispersion was applied to the spectra; as Trager et al. (1998, their Fig. 3) demonstrate, such a correction for globular clusters is negligible.

Before measuring the H$_{\text{IR}}$ and Ca$_{\text{IR}}$ line indices, our observed standards and target 47 Tuc spectra were first smoothed with a $\sigma = 103$ km s$^{-1}$ Gaussian and rebinned to 0.623 Å pixel$^{-1}$, in both cases to parallel Jones (1996b). The H$_{\text{IR}}$ and Ca$_{\text{IR}}$ equivalent widths are measured as detailed in §3 of Jones & Worthey (1995). Flanking blue and red pseudocontinuums peaks, usually associated with the immediately adjacent blue and red shoulders of the relevant absorption line, were identified; the equivalent widths were then measured relative to the continuum formed by connecting the two pseudocontinuum peaks. For H$_{\text{IR}}$, the blue pseudocontinuum was associated with the local maximum between 4329 and 4336 Å, while the red pseudocontinuum was associated with the maximum in the 4346–4350 Å window; for Ca$_{\text{IR}}$, the corresponding windows were 4218–4222 Å and either 4230–4232 Å (early spectral types) or 4242–4246 Å (later spectral types). Figure 1 shows the pair of integrated 47 Tuc spectra in the region of both the H$_{\text{IR}}$ and Ca$_{\text{IR}}$ indices: the associated flanking pseudocontinuums are similarly noted. The equivalent width was derived via a simple Simpson’s rule algorithm, summing the area associated with the 7 0.623 Å pixels centered on the minimum of the high-resolution absorption feature—Gaussian fitting to the line profiles was not employed in our analysis, again, in order to maintain consistency with Jones (1996b). The derived equivalent widths of Figure 1 are consistent, from night to night, at the 2%–3% level.

For the Fe 4668 measurement, the 13 standards and 47 Tuc spectra were smoothed with a $\sigma = 250$ km s$^{-1}$ Gaussian to match the Lick/IDS resolution. Adjacent blue and red continua were determined from the mean flux in the 4611.50–4630.25 and 4742.75–4756.500 Å windows, respectively. Using the continuum defined by the line connecting the mean of these two windows, the equivalent width was then derived by integrating the absorption feature over the 4634.00–4720.25 Å window. The adopted windows are marginally different from those defined by Worthey et al. (1994, Table 1); they reflect those adopted in the 1997 edition of the Lick/IDS stellar catalog (Trager et al. 1998).

Comparison of the equivalent widths derived from our 13 standards with those tabulated in the coude feed spectral library (H$_{\text{IR}}$ and Ca$_{\text{IR}}$) and Lick/IDS library (Fe 4668) revealed that the two systems were on the scale and no further corrections were needed to bring the systems into agreement—i.e., both groups were measuring identical equivalent widths for the same standards—and therefore, our measured 47 Tuc equivalent widths could be used as is in comparing against the model age-metallicity diagnostic diagrams of Jones & Worthey (1995) and Jones (1996a).

A quirk of the line-measuring code employed by Jones (1995, 1996a, 1996b), itself an offspring of that used by Rose (1994 and earlier papers), is that the equivalent width derivation requires 3 pixels on either side of the absorption-feature minimum (itself 1 pixel)—i.e., while the pixel center-to-center window is the 3.74 Å referred to throughout this paper (and earlier Rose and Jones papers), the effective area over which the integration is acting corresponds to 7 pixels, or 4.36 Å.
Evidence to this effect is presented in Figure 2, in which our standard star Ca equivalent widths (x-axis) are directly comparable, with the mean offset between the two samples being only $0.010 \pm 0.006$ Å, a factor of $\sim 3$ times smaller than the typical uncertainty associated with pseudocontinua placement and night-to-night variations (recall Fig. 1). Identical conclusions hold for the other line indices in our study. Our measured (and adopted) 47 Tuc equivalent widths are therefore $1.032 \pm 0.040$ Å ($H_{\text{IIR}}$), $1.042 \pm 0.030$ Å ($Ca_{\text{IIR}}$), and $1.95 \pm 0.45$ Å (Fe 4668), where the uncertainties reflect those due to pseudocontinuum placement and, to a lesser degree, the scatter derived from repeated measurements of the set of standards.

3. DISCUSSION

Following the prescription outlined by Jones & Worthey (1995) and Jones (1996b), the Worthey (1994) population synthesis models were used to predict $H_{\text{IIR}}$, $Ca_{\text{IIR}}$, and Fe 4668 line index strengths, as a function of age and metallicity [Fe/H], for a grid of single-burst stellar populations. Twenty-four realizations, spanning ages 2–17 Gyr and metallicities $[Fe/H] = -0.50$ to $+0.50$, were made; the full set of 24 models were then incorporated into the $H_{\text{IIR}}$ versus $Ca_{\text{IIR}}$ age-metallicity diagnostic grid shown in Figure 3. While not perfectly orthogonal, this pair of high-resolution, Rose-style indices does provide adequate separation of age and metallicity, with a minimum of degeneracy. The four filled symbols represent the same set of low-luminosity ellipticals shown in the earlier analysis of Jones (1996a) but now smoothed to the same $\sigma = 103$ km s$^{-1}$ resolution adopted by Jones (1996b) and the present study. As discussed previously (Jones 1996a), these four galaxies represent a (luminosity-weighted) solar metallicity-age sequence spanning the range 2–12 Gyr.

The open star in Figure 3 represents our new 47 Tuc data point; unlike the four galaxies, 47 Tuc has an independent age ($14 \pm 1$ Gyr) and metallicity ($[Fe/H] \approx -0.7$) determination derived from isochrone fitting to the CMD (Richer et al. 1996; Salaris & Weiss 1998). It should be immediately clear that the spectroscopic age of 47 Tuc, as determined by the age-sensitive $H_{\text{IIR}}$ line index, is inconsistent with its CMD age at the $\sim 4 \sigma$ level, being $\sim 0.2$ Å lower than expected for this 14 Gyr old simple stellar population. This $0.2$ Å $H_\gamma$ discrepancy was previously noted by Rose (1994, § 5.1), although not in the context of age dating its integrated spectrum. On the other hand, it is somewhat reassuring that the metallicity inferred from Figure 3 (i.e., $[Fe/H] < -0.5$) is consistent with that derived from the CMD (Richer et al. 1996).

Figure 4 shows the $H_{\text{IIR}}$ versus Fe 4668 age-metallicity diagnostic diagram as presented by Jones & Worthey (1995, their Fig. 2); the same 19 models used in their analysis are incorporated into our grid. The only (subtle) difference between our diagram (Fig. 4) and that of Jones & Worthey is that, in the latter, the spectra were smoothed to $\sigma = 80$ km s$^{-1}$ (to match the resolution of their M32 spectrum),

$^7$ Salaris & Weiss (1998), using a-element-enchanced stellar models, have recently revised the age of 47 Tuc from the canonical (scaled solar abundance) Richer et al. (1996) value of $14 \pm 1$ Gyr to the lower value of $9 \pm 1$ Gyr. On the surface, this worsens the spectroscopic vs. CMD age discrepancy of Fig. 3, although the comparison is perhaps not a fair one, since Worthey's (1994) synthesis models are (necessarily) tied to models and stellar data that are likewise of scaled solar abundances. Similarly, the post-$Hipparcos$ globular cluster distance scale appears to favor a 2–3 Gyr reduction in the mean age of the oldest globular clusters (Chaboyer et al. 1998); again, this strengthens our conclusion regarding the spectroscopic age of 47 Tuc, although, to be fair, as before, we retain the Richer et al. (1996) result as the most representative one against which to compare our results.

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**Fig. 1.** Integrated 47 Tuc spectra, smoothed to a velocity resolution of $\sigma = 103$ km s$^{-1}$ to match Jones (1996b), acquired the nights of October 20 (solid lines) and October 21 (dotted lines). The primary high-resolution line indices employed in our study—$H_{\text{IIR}}$ (top) and $Ca_{\text{IIR}}$ (bottom)—are shown, as are the adopted neighboring pseudocontinua. The derived equivalent widths are consistent, from night to night, at the 2%–3% level.

**Fig. 2.** Comparison of published Ca $\text{I}_{\text{IR}}$ equivalent widths (x-axis) vs. those of the present study (y-axis), for the standard stars in common. Clearly the two systems are directly comparable, with the mean offset between the two samples being only $0.010 \pm 0.006$ Å, in the sense of Jones minus present study.
while in the present study, recall that \( \sigma = 103 \) km s\(^{-1}\) Gaussian was employed (to match the spectra and models of Jones 1996b). Again, the model sequences of Figure 4 clearly demonstrate the almost perfectly orthogonal nature of the H\(_{\text{K}}\) and Fe 4668 line indices in the age-metallicity plane.

As in Figure 3, the filled square represents the Jones & Worthy (1995) observation of M32, while the open star shows our new 47 Tuc data point. As was the case for the pair of Rose-style, high-resolution line indices (Fig. 3), in H\(_{\text{K}}\) versus Fe 4668 the anomalously low H\(_{\text{K}}\) in the integrated spectrum of 47 Tuc results in a spectroscopic age (\( \gtrsim 20 \) Gyr) that is clearly discrepant with the CMD age (14 \( \pm \) 1 Gyr).

Is there some way in which to reconcile the spectroscopic versus CMD age discrepancy? As discussed by Rose (1994), virtually every line index in the integrated spectrum of 47 Tuc appears perfectly well behaved, except the anomalously strong CN bands and the anomalously weak H\(_{\text{K}}\) line. Jones (1996b) speculated that perhaps the H\(_{\text{K}}\) “problem” was being caused by CH contamination in the H\(_{\text{K}}\) line; because the central region of 47 Tuc (i.e., the region over which our integrated spectrum was obtained) is replete with CN-strong giants (Norris & Freeman 1979; Da Costa 1997) and there exists the well-known CN-CH anticorrelation for CN-strong giants (Norris, Freeman, & Da Costa 1984), a scenario was envisaged whereby H\(_{\text{K}}\) might be weaker in CN-strong (CH-weak) stars. Jones (1996b), though, was able to show, using a sample of 11 CN-strong and CN-weak, giant- and horizontal-branch stars from M71 (a cluster similar to 47 Tuc), that this initial hypothesis is not supported by the data.

The most obvious speculative source of the discrepancy is that some unidentified source of H\(_{\text{K}}\) emission is acting to “fill in” the H\(_{\text{K}}\) absorption feature. Hesser & Shawl (1977) provide an upper limit to the emission flux at H\(_{\text{K}}\) of \( F(\text{H}K) \lesssim 1.3 \times 10^{-11} \) ergs cm\(^{-2}\) s\(^{-1}\). Here we have used their most restrictive data set—i.e., \( C_1 \approx 26.3 \) s\(^{-1}\) (from their 1975 August 22 observations), coupled with the definition \( F(\text{H}K) \approx 5 \times 10^{-13} C_1 \) ergs cm\(^{-2}\) s\(^{-1}\) from Smith, Hesser, & Shawl (1976). Now, the core of 47 Tuc, with \( M_\epsilon \approx +6 \) (and ignoring reddening), corresponds to a flux of \( \approx 1.6 \times 10^{-13} \) ergs cm\(^{-2}\) s\(^{-1} \) Å\(^{-1}\). So, the Hesser & Shawl upper limit of \( 1.3 \times 10^{-11} \) ergs cm\(^{-2}\) s\(^{-1}\) corresponds to 1.3/1.6 = 0.8 Å of equivalent width at H\(_{\text{K}}\). Several simplifying assumptions must be made to go from Hz to H\(_{\text{K}}\)—specifically, under case B conditions and a temperature of 10,000 K, radiative recombination leads to an intrinsic ratio \( L(\text{Hz})/L(\text{H}K) \approx 6.5 \), which gets reduced by a factor of 1.7, reflecting the ratio of continuum flux at H\(_{\text{K}}\) to that at H\(_{\text{K}}\) (employing the Worthey 1994 models). In other words, H\(_{\text{K}}\) is a factor of 3.8 times weaker than H\(_{\text{K}}\); recalling the constraint at Hz of \( \lesssim 0.8 \) Å, this corresponds to \( \lesssim 0.21 \) Å of equivalent width at H\(_{\text{K}}\).

From Figures 3 and 4, we can see that the H\(_{\text{K}}\) “discrepancy” amounts to \( \sim 0.17 \) Å in that we a priori expected an equivalent width of \( \sim 1.20 \) Å to match the known CMD age of 47 Tuc, as opposed to the \( \sim 1.03 \) Å observed. Recalling that the inferred upper limit of emission fill-in at H\(_{\text{K}}\) (from the previous paragraph) was \( \lesssim 0.21 \) Å, we can see that the requisite \( \lesssim 0.17 \) Å of emission needed to reconcile the CMD and spectroscopic ages is not entirely excluded by the Hesser & Shawl (1977) observations, although little room is left to maneuver should new Hz emission observations push this limit even lower.

The situation regarding the anomalously low H\(_{\text{K}}\) index in 47 Tuc remains as it was at the time of the Rose (1994) and Jones (1996b) studies—i.e., 47 Tuc appears normal in vir-
tually every line index, except Hγ, and to date no satisfactory explanation has been put forth. Emission fill-in has not been entirely excluded, but the constraints are tight, as shown above. Should such emission prove to be the ultimate resolution of the discrepancy, though it will beg the question as to exactly which mechanism is responsible and why it differs from the local calibrating stars used to derive the model sequences of Figures 3 and 4.

4. SUMMARY

From the outset, our goal was a simple one: to provide an independent test of the Jones & Worthey (1995) Hγ/HR − Fe 4668 diagnostic (and the Jones 1996a Hγ/HR − Ca i HR diagnostic) as a tool for breaking the long-standing age-metallicity degeneracy plaguing integrated spectra of stellar populations. Such a test can only be done (properly) upon systems with independently derived ages and metallicities; local metal-rich globular clusters with accurate, deep CMDs provide an ideal test bed. Our new high signal-to-noise ratio, high-resolution, integrated spectrum of 47 Tuc shows anomalously low Hγ absorption, which, when tied to the diagnostic models of Jones & Worthey (1995), shows for the first time that the inferred spectroscopic age is well in excess of 20 Gyr. This is clearly at odds with the CMD age of 14 ± 1 Gyr. No suitable explanation of the source of this discrepancy has been found, despite the best efforts of Rose (1994) and Jones (1996b). Emission, amounting to ~0.17 Å of the equivalent width at Hγ, is required to reconcile the discrepancy. Such emission is not excluded by the Hesser & Shawl (1977) observations of 47 Tuc (which set an upper limit of ~0.21 Å at Hγ), but if this is the responsible mechanism, it must be lurking marginally below the limit set by these early Fabry-Perot observations. Clearly, a deeper revisit is called for.

It is true that the Jones & Worthey (1995) Hγ/HR − Fe 4668 age-metallicity diagnostic will remain an invaluable tool for age dating integrated spectra of early-type systems, but perhaps the most important conclusion to take from our simple test of the technique is that it is not infallible. Clearly, it will be imperative to extend our analysis to a larger sample of metal-rich globular clusters, Galactic open clusters, and star clusters in the Magellanic Clouds—such an analysis will demonstrate whether 47 Tuc is a pathological case or whether the inconsistent spectroscopic age derived here is indicative of an endemic—and currently underappreciated—flaw in the technique.

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