STRÖMGREN PHOTOMETRY OF GLOBULAR CLUSTERS: THE DISTANCE AND AGE OF M13, EVIDENCE FOR TWO POPULATIONS OF HORIZONTAL-BRANCH STARS

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ABSTRACT

We present deep CCD photometry of the globular cluster M13 (NGC 6205) in the Strömgren uvbyβ system and determine a foreground reddening of \(E(b - y) = 0.015 \pm 0.01\) mag. From a fit to the main sequence of metal-poor subdwarfs with Hipparcos parallaxes, we derive \((m - M)_V = 14.38 \pm 0.10\), which implies an age near 12 Gyr assuming \([\text{Fe}/\text{H}] = -1.61\) and \([\alpha/\text{Fe}] = 0.3\). The distance-independent \([b - y]_0, c_a\) diagram indicates that M13 and metal-poor field subdwarfs of similar metallicity must be coeval to within \(\pm 1\) Gyr. In addition, we find that, at any given \((b - y)_0\) color, there is a large spread in the \(c_a\) index for M13 red giant branch (RGB) stars. We suspect that this scatter, which extends at least as faint as the base of the RGB, is most likely due to star-to-star variations in the atmospheric abundances of the CNO elements. We also note the existence of what appears to be two separate stellar populations on the horizontal branch of M13. Among other possibilities, it could arise as the result of differences in the extent to which deep mixing occurs in the precursor red giants.

Subject headings: globular clusters: general — globular clusters: individual (M13) — stars: evolution — stars: horizontal-branch — stars: Population II

1. INTRODUCTION

Despite a concerted effort by many researchers over the past few decades (see, e.g., the reviews by VandenBerg, Bolte, & Stetson 1996, Stetson, VandenBerg, & Bolte 1996, Sarajedini, Chaboyer, & Demarque 1997, and references therein), it has not been possible to reach a consensus on either the absolute or the relative ages of the Galactic globular clusters (GCs). Much of the controversy in this field can be traced to the difficulty of determining reliable values for the basic parameters that enter into a determination of the cluster age, such as distance, reddening, overall metallicity, and detailed abundance patterns.

In this respect, the Strömgren uvbyβ photometric system offers unique advantages over broadband photometry since it can provide precise estimates of \(T_{\text{eff}}, [\text{Fe}/\text{H}],\) and surface gravity for F and G stars, as well as the reddening, on a star-by-star basis (see Schuster & Nissen 1989a and references therein). Furthermore, databases of quite homogeneous Strömgren photometry exist for large samples of stars, both metal poor and metal rich (Schuster & Nissen 1988; Olsen 1983, 1984). Many of these stars have new, high-precision determinations of their parallaxes from the Hipparcos mission, making them particularly useful for distance determinations via the main-sequence–fitting technique. Moreover, since the Strömgren system includes a \(u\) filter, which is entirely on the short-wavelength side of the Balmer jump, it can be used to probe the temperatures and gravities of horizontal-branch (HB) stars, including those on extended blue HBs (de Boer, Schmidt, & Heber 1995).

As is well known, considerable evidence has accumulated during the past \(\sim\)20 years that indicates that red giants in globular clusters have mixed much deeper into their nuclear-burning interiors than canonical models predict—see, e.g., Kraft et al. (1997, 1998) and the reviews by Da Costa (1997) and Kraft (1994) for discussions of the extensive literature on this subject. Indeed, in order to explain the observed abundance patterns of C, N, O, Na, Al, and Mg (also see Pilachowski et al. 1996 and Shetrone 1996), it seems to be necessary for the mixing to penetrate so closely to the H-burning shell that some helium must also be dredged up into the surface layers during the evolution (see, e.g., Langer, Hoffman, & Zaidins 1997; Sweigart 1997a, 1997b; Cavallo, Sweigart, & Bell 1998). As discussed in Sweigart (1997b), even small amounts of He mixing could have large effects on the HB and account for at least part of the second-parameter phenomenon (i.e., the diversity in HB morphology among GCs having very similar chemical compositions).

2. OBSERVATIONS AND DATA REDUCTION

All of the M13 observations were obtained using the Nordic Optical Telescope on La Palma, Canary Islands, and Strömgren uvbyβ filters during the period from 1995 June 27 to July 2. The weather was excellent during the observing run, giving seeing values between 0′′.43 and 0′′.8, with a mean value close to 0′′.60. The detector used was a SITe 1024 square chip providing a total field of 3′ × 3′. All photometric reductions of the cluster frames were carried out using DAOPHOT, ALLSTAR, ALLFRAME, and DAOGROW (see Stetson 1987, 1990, 1994). In each frame, approximately 20,000 stars were detected. For the standard stars, the residuals in the transformation from the instrumental to the standard system were \(V = 0.004, (b - y) = 0.005, m_1 = 0.008, c_1 = 0.010,\) and \(\beta =\)
0.008. For M13, the error in the zero point for each filter is estimated to be of order 0.01 mag. The data reduction procedures will be described in more detail in a forthcoming paper.

3. CLUSTER PARAMETERS

Before attempting to determine the distance to M13, it is necessary to know the amount of interstellar absorption toward the cluster as well as the stellar iron content (preferably the estimated to be of order 0.01 mag). The data reduction procedures will be described in more detail in a forthcoming paper.

3.1. Cluster Distance and Age

Ideally, the distance to M13 would be determined by a main-sequence fit of the color-magnitude (C-M) diagram for the unevolved cluster stars to a large sample of local subdwarfs having the same metallicity as the cluster and very precise parallaxes. Unfortunately, the number of subdwarfs with [Fe/H] \( \approx -1.6 \) and with relative errors in their parallaxes at the few percent level remains small. Potentially useful subdwarf candidates were selected from the list of Nissen, Hög, & Schuster (1997), with metallicities derived from Strömgren photometry and parallaxes determined by Hipparcos. As in the case of M13, the individual reddening and metallicities of the subdwarfs were determined using the calibrations of Schuster & Nissen (1989a).

Following the usual procedure (see, e.g., VandenBerg et al. 1996), the dereddened colors of the subdwarfs were individually adjusted to compensate for the (small) differences in their metallicities relative to that of M13 using the isochrones of VandenBerg et al. (1998), as transformed to the Strömgren system using Kurucz (1992) color transformations: R. Bell (1998, private communication) has obtained much better agreement of his color-temperature relations. The fit of the M13 [(\( u - y \))\(_0\), \( V \)] and [(\( u - y \))\(_0\), \( u \)] C-M diagrams to the resultant “monometallicity” subdwarf sequence, we used stars with \( (\pi / \sigma_{\pi}) \leq 0.07 \), where \( \pi \) is the parallax, and photometric metallicities in the range \( -1.69 \leq [\text{Fe/H}] \leq -1.57 \). Consequently, the model-based color corrections are all quite small for these stars. Furthermore, by adopting such stringent constraints on the relative parallax error, the Lutz-Kelker corrections (Lutz & Kelker 1973; Lutz 1979) amount to only a few hundredths of a magnitude, at most, and possible systematic biases for the whole sample are negligible as well (see the discussion by Pont et al. 1998). We applied Lutz-Kelker corrections to the subdwarfs using the formula given by Hanson (1979) with \( n = 2 \). Figure 1 illustrates the [(\( u - y \))\(_0\), \( V \)] diagram for M13 with the subdwarfs overplotted. The main-sequence fit yields \( (m - M)_V = 14.44 \) and \( (m - M)_u = 14.49 \) with an uncertainty of \( \pm 0.10 \) mag.

Isochrones from VandenBerg et al. (1998) for [Fe/H] = -1.61, [\( \alpha / \text{Fe} \)] = 0.3, and ages of 10, 12, and 14 Gyr have also been superposed on the data in Figure 1. These indicate

Two of the stars used in the main-sequence fit (HD 64090 and HD 188510) are listed by Gratton et al. (1997) and Pont et al. (1998) as spectroscopic binaries or radial velocity variables. However, Carney et al. (1994) have taken 19 velocity measurements for HD 188510 over 8.2 years, and they find no indication of radial velocity variations (rms \( \approx 0.8 \) km s\(^{-1}\)), while five out of six measurements of the velocity of HD 64090 by Stryker et al. (1985) are in excellent agreement. Stryker et al. (1985) quote a semiamplitude limit of 14 km s\(^{-1}\) for their sensitivity; their one discrepant velocity value differs from the mean of the other five by 27.4 km s\(^{-1}\). Moreover, regardless of which C-M diagram is used in the subdwarf fit, these two stars show no sign of being “overluminous” with respect to the other two that we have used (HD 34328 and HD 25329) and the main-sequence fiducial. Therefore, if HD 64090 and/or HD 188510 are binaries, the secondary component(s) must be much fainter than the primaries.

Because of the high precision of the parallaxes for the selected stars, the choice of \( n \) has no significant impact on the derived distance modulus.
that the age of M13 is close to 12 Gyr. The reduction in age from values near 14–16 Gyr that were commonly obtained a few years ago is due less to revisions in the cluster distance than to improvements in the stellar models. Indeed, the M13 distance modulus derived here is within 0.1 mag of the values determined by, e.g., Richer & Fahlman (1986) and Buckley & Longmore (1992) in the pre-
*Hipparcos* era. Instead, it is the use of improved opacities and an equation of state that treats nonideal effects (e.g., Proffitt 1993), the adoption of a revised bolometric correction scale (see Vandenberg 1997), and the assumption of [Fe/H] = 0.3, rather than a scaled-solar heavy-element mix, that is primarily responsible for the reduced GC ages. It should be noted that the present models do not include the effects of helium diffusion, which can be expected to reduce the age at a given turnoff luminosity by ~1 Gyr (see, e.g., Proffitt & Vandenberg 1991).

4. THE [(b−y)0, c0] DIAGRAM

Having extensive Strömgren photometry for M13 stars fainter than the main-sequence turnoff allows us to determine whether the cluster differs significantly in age from field stars of similar metallicity. For F and G stars, c0 = c1 − 0.2E(b−y) is a measure of the size of the Balmer jump, which, in turn, is a measure of surface gravity and hence of evolutionary state. Therefore, the c1 index can be used to distinguish between evolved and unevolved stars and to determine the ages of stars near the turnoff (see, e.g., Fig. 7 in Vandenberg & Bell 1985), independently of any knowledge of their distances. This approach has been used by Schuster & Nissen (1989b) to determine ages for a large sample of metal-poor field stars. In Figure 2, we have overplotted the photometry for stars in their catalogs having metallicities between −1.4 and −1.9 on the [(b−y)0, c0] diagram for M13. It is immediately obvious from this figure that the field stars follow the cluster locus closely, indicating that the two stellar populations must have very nearly the same age. The maximum difference between the turnoff c0 values is ±0.025 mag, which translates into an age difference of ∼±1 Gyr, which, we emphasize, is completely independent of the adopted distance scale. We cannot, of course, exclude the possibility that some of the field stars on the lower main sequence are older, only that none of the evolved stars has a greater age than M13.

A surprising feature of the data plotted in Figure 2 is that, at any given (b−y)0 color, the M13 giant-branch stars exhibit a large spread (0.1–0.15 mag) in the c0 index. Since we have no spectra for the observed stars, it is not clear at this point how these c0 variations should be interpreted. However, as noted in § 1, it is well known that stars on the M13 red giant branch (RGB) encompass large variations in the C, N, O, Mg, and Al abundances, most likely due to deep mixing during the post–main-sequence evolution. Star-to-star variations in these elements are the most likely cause of the c0 variations, in view of the fact that several investigations (Bond 1980; Anthony-Twarog & Twarog 1994; Anthony-Twarog, Twarog, & Craig 1995) have demonstrated that stars with strong CH and CN bands can have significantly lower c1 indices than similar stars of normal CH and CN strength. Spectroscopic observations of the stars showing extreme c1 values are needed to identify the elements responsible for the variations.

If the large spread in the c1 observations is due to variations in the elemental abundances due to mixing, then Figure 2 would suggest that such mixing commences near the base of the red giant branch. One cannot help but speculate that a thermal instability in the H-burning shell might be at least partly responsible for the observed scatter since Von Rudloff, Vandenberg, & Hartwick (1988) have shown that the greatest potential for such an instability occurs just as a star begins to ascend the giant branch. This possibility should be investigated further.

5. HORIZONTAL BRANCH

We now turn to a brief discussion of the properties of the observed horizontal branch. In Figure 1, a zero-age horizontal-branch (ZAHB) locus (Vandenberg et al. 1998), which represents the extension of the isochrones to the core He-burning phase, has been superposed on the data on the assumption of the adopted distance modulus and reddening. It is apparent that the coolest of the HB stars are reasonably well matched by the model ZAHB. However, at (u−y)0 < 0.95, the HB stars appear to be ~0.4 mag “overluminous” compared with the theoretical locus. We note that this “anomaly” has also been seen by B. Dorman et al. (1998, private communication) in their *Hubble Space Telescope* (HST) observations of M13 (using the F336W and F555W filters). In fact, a preliminary analysis of the Strömgren data that we have in hand for NGC 288 and NGC 6752, which both possess blue HBs, shows the same unexpected morphology. This cannot be explained in terms of evolution away from a ZAHB since the evolution is slowest near the zero-age locus, and therefore most stars should be found adjacent to it. Unless the discrepancy is due to a problem with the color–*Teff* relations derived from model atmospheres, which seems unlikely, a different ZAHB must apply to these stars; i.e., M13 (as well as NGC 288 and NGC 6752) must possess at least two distinct HB populations.

At first sight, these observations appear to be in remarkable agreement with the recent predictions by Sweigart (1997a, 1997b), who has demonstrated that, if red giants undergo sufficiently deep mixing so as to modify their envelope helium abundances appreciably, then their descendants on the HB
should be bluer and more luminous than predicted by canonical models. In fact, there is some indication in his calculations (compare, e.g., Figs. 7 and 9 in Sweigart 1997b) that, for the hottest HB stars, the He-mixed models and those based on standard assumptions will nearly coincide. Thus, the near match of the canonical ZAHB with the lower bound of the M13 stars fainter than \( V \sim 17.7 \) (see Fig. 1) can be understood. On the other hand, Rood et al. (1998) have found that there is no apparent discrepancy between canonical HB models and M13’s HB when comparisons between the two are made on C-M diagrams involving bands that are bluer than the \( \text{HST F336W} \) filter (which is close to the Strömgren \( u \)). So, at the present moment, it is not clear how this will be resolved.

Finally, we note that in a \((u - \gamma, u)\) diagram, both the ZAHB appropriate to the coolest blue HB stars and the locus of subgiant stars are very nearly horizontal and very well defined; thus, it is easy to measure the \( u \) luminosity difference (\( \Delta u \)) to high accuracy. From the isochrones of VandenBerg et al. (1998), we estimate that \( \Delta u \) changes at a rate of \( \pm 0.065 \) mag Gy \(^{-1}\). One such precision available here, we estimate that this method will provide the possibility to measure the age difference between clusters of similar metallicity to better than 0.5 Gy.

6. SUMMARY

The capability of Strömgren photometry to reveal important new features of GC C-M diagrams is undeniable. In this investigation of M13, we have found the following: (1) The reddening of M13 is \( E(b - y) = 0.015 \pm 0.01 \), which corresponds to \( E(B - V) = 0.021 \pm 0.014 \). (2) The cluster distance is \( (m - M)_0 = 14.38 \pm 0.10 \), based on C-M diagram fits to local subdwarfs with \( \text{Hipparcos parallaxes} \). This implies an age of 12 \( \pm 1.5 \) Gy, according to recent theoretical isochrones for \([\text{Fe/H}] = -1.61\) and \([\alpha/\text{Fe}] = 0.3\), which do not take He diffusion into account. (3) There is a large spread in \( c_1 \) for stars from the base to the tip of the RGB, which is probably indicative of star-to-star variations in the CNO abundances. (4) Field stars with metallicities similar to that of M13 are found to be coeval with M13 to within \( \pm 1 \) Gy. (5) The HB shows evidence of two distinct populations, which may be related to the observed scatter in \( c_1 \) on the RGB. It is also possible that we are seeing the signature of He mixing in upper RGB stars, as discussed by Sweigart (1997a, 1997b).

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