

## COLOR-MAGNITUDE PHOTOMETRY OF 47 TUCANAE TO $M_V = +9$

WILLIAM E. HARRIS<sup>1</sup>

Physics Department, McMaster University

JAMES E. HESSER<sup>1</sup>

Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics

AND

BRUCE ATWOOD

Cerro Tololo Inter-American Observatory

Received 1982 October 4; accepted 1983 February 7

### ABSTRACT

We present a color-magnitude diagram, obtained with the Cerro Tololo Inter-American Observatory vidicon system in direct mode, for the main sequence of 47 Tucanae (= NGC 104 = C0021 – 723), to a limiting magnitude of  $V = 22$  ( $M_V = +9$ ). The observed scatter along the main sequence is  $\sigma(B - V) = 0.04$  mag, consistent with the internal errors of measurement. Isochrone fits with VandenBerg's recent stellar models are consistent with his conclusion that 47 Tuc has an age of  $15\text{--}18 \times 10^9$  yr and a heavy-element abundance  $Z \approx 0.006$ .

*Subject heading:* clusters: globular

### I. INTRODUCTION

The long-standing problem of measuring accurate ages and compositions for the galactic globular clusters has recently acquired fresh importance. Some recent discussions of the cluster ages (Carney 1980; Demarque 1980) have suggested age differences between clusters of several billion years. Other discussions, using very much the same basic observational material but with different analytical techniques and theoretical input (see, e.g., Sandage 1982; VandenBerg 1983) have concluded that the ages of the clusters are closely similar and therefore that the galactic halo developed at a sharply defined epoch.

From the observational side, a key obstacle is the difficulty of measuring reliable luminosities and colors of extremely faint, often crowded stars to levels well below the main-sequence turnoff. Random scatter and calibration uncertainties traditionally have severely limited the reliability of isochrone fits for virtually all clusters (cf. Sandage and Katem 1977; Cannon 1981a; Shipman 1981; VandenBerg 1981). Fortunately, with the more precise photometry for large numbers of stars that the modern generation of electronic detectors should produce, the age measurement problem (as well as issues such as observational versus intrinsic scatter in the color-magnitude diagram [CMD] or internal chemical homogeneity) may be addressed more securely. In this

*Letter*, we report the first results from a recently completed observational program with the Cerro Tololo Inter-American Observatory (CTIO) SIT vidicon, intended to obtain deep  $BV$  photometry in fields around several LMC and galactic globular clusters. Complete results for all the program clusters are to be presented in subsequent papers. Here, we discuss a CMD reaching  $V \approx 22$  ( $M_V \approx +9$ ) for 47 Tucanae and interpret it in the context of the globular cluster age problem.

### II. OBSERVATIONAL MATERIAL

During two observing runs with the CTIO 4 m telescope (1980 November 8–10 and 1981 December 18–21), we acquired frames in  $B$  and  $V$  with the S-20 SIT vidicon camera (Atwood *et al.* 1979) at the Ritchey-Chrétien focus. We operated the detector in its “equilibrium” mode (continual readout, summing many short exposures) to allow a dynamical range of  $\geq 5$  mag and a bright limit of  $V \approx 17$  without saturation. Most frames (the 1981 data) were  $340 \times 340$  pixels square ( $0''.2$  pixel<sup>−1</sup>), while the few additional exposures from the preliminary 1980 run were  $256 \times 256$  pixels. The seeing varied from  $\sim 1''.5$  to  $3''$  from night to night, yielding well-sampled image profiles. We observed six 47 Tuc fields in total (some partially overlapping), at radii of  $\sim 16'$  from the cluster center (or  $\sim \frac{1}{3}r_t$ ; e.g., Illingworth and Illingworth 1976), far enough out to avoid serious crowding problems but close enough that a large fraction of the stars in each frame would be cluster members (cf. Hesser and Bell 1980). Local photoelectric sequence standards in the range  $17 < V < 19$  from Hesser and

<sup>1</sup>Visiting Astronomer, Cerro Tololo Inter-American Observatory and Kitt Peak National Observatory, which are operated under contract with the National Science Foundation.

TABLE 1  
VIDICON FRAMES AND CALIBRATION STANDARDS

Frame Pair	Date	Exposure (minutes)	Standards in Frame <sup>a</sup>
2006 <i>B</i> , 2007 <i>V</i> ...	1980 Nov 10–11	40	HH 9088 (17.03, 1.52)
1001 <i>B</i> , 1002 <i>V</i> ...	1981 Dec 18–19	35	HH 9088 (17.03, 1.52)
2008 <i>B</i> , 2009 <i>V</i> ...	1981 Dec 19–20	35	HH 9088 (17.03, 1.52)
2010 <i>B</i> , 2011 <i>V</i> ...	1981 Dec 19–20	35	HH 9088 (17.03, 1.52)
3011 <i>B</i> , 3012 <i>V</i> ...	1981 Dec 20–21	18	HH 9004 (17.42, 0.62) 9005 (17.16, 0.64)
4010 <i>V</i> , 4011 <i>B</i> ...	1981 Dec 21–22	18	C12 (18.36, 0.57) C13 (17.84, 0.57)

<sup>a</sup>Quantities in parentheses give the smoothed photographic ( $V$ ,  $B - V$ ) values (Hesser and Hartwick 1977; Cannon 1981*b*) that were adopted to calibrate the instrumental zero points in each frame. The first four exposure pairs listed are not all at identical locations, though they all overlap at least partially.

TABLE 2  
INTERNAL PHOTOMETRIC ERRORS

$V$ Range	$\sigma_V$	$\sigma_{B-V}$
< 18 .....	0.015	0.020
19 .....	0.025	0.030
20 .....	0.055	0.065
21 .....	0.100	0.135
22 .....	0.18:	0.23:

Hartwick (1977) and Cannon (1981*b*) were used in each frame to set the photometric zero points. Following initial dark-count subtracting and flat-fielding of the raw data frames with the CTIO La Serena software facilities (Schaller *et al.* 1978), we completed all the photometric reductions (profile fitting and relative magnitudes) with the RICHFLD software (Tody 1981) at Kitt Peak National Observatory (KPNO).

Table 1 lists our six program fields. The first four overlap to various degrees, and stars in common between these frames were used to ensure that they were all on the same *internal* magnitude scale system to within  $\pm 0.02$  mag. These “frame versus frame” comparisons were also used, along with one short-exposure and long-exposure pair of field no. 1 from the 1980 run, to derive estimates of the internal photometric errors (Table 2). (The short/long pair also verified the high linearity of SITs operated in equilibrium mode as reported previously, e.g., by Lynds 1975, Butcher and Oemler 1978, Atwood *et al.* 1979.) Color equations relating the instrumental ( $v$ ,  $b - v$ ) and standard ( $V$ ,  $B - V$ ) systems were determined from frames of three fields in the globular cluster NGC 1904 (Stetson and Harris 1977), which contains both blue horizontal-branch and red-giant stars at similar magnitudes. (The NGC 1904 frames were smaller [ $256 \times 256$  pixels] than most of our 47 Tuc frames, permitting a much brighter

saturation limit.) Use of seven blue and 13 red stars in NGC 1904 within  $15.7 < V < 17.5$  and  $-0.02 < (B - V) < 1.00$  led to the instrumental transformations  $v = V + (0.055 \pm 0.03)(B - V) + \text{const}$ , and  $(b - v) = (1.00 \pm 0.03)(B - V) + \text{const}$ . We emphasize that the *zero* points of our 47 Tuc photometry depend only on the local standards, and not in any way on NGC 1904.

### III. COLOR-MAGNITUDE DIAGRAM

Our CMD for all six fields in Table 1 is shown in Figure 1. Several comments on its characteristics can be made:

1. The main-sequence locus is more precisely defined to fainter  $M_V$  levels than for any other globular cluster yet observed. (A similarly precise study of the very metal-poor cluster M15 is described by Sandage and Katem 1977, though it does not reach the same  $M_V$  limit.) Over  $17 < V < 20$ , the rms dispersion in the *observed* CMD about a mean line drawn through the main sequence is  $\sigma(B - V) = 0.042$ . The *intrinsic* star-to-star differences are therefore at least that small and are probably  $\leq \pm 0.02$ , given the internal random errors (Table 2) and the possible ( $\leq 0.02$ ) frame-to-frame zero point differences also entering Figure 1. This result for the “cosmic scatter” along the main sequence agrees with other independent photographic studies for M15, M3, and 47 Tuc (Sandage and Katem 1977, 1982; Hesser, Egles, and Liller 1983) and also bears on the interpretation of star-to-star CN-strength differences reported for the 47 Tuc turnoff region stars (Hesser and Bell 1980; Bell, Hesser, and Cannon 1983).
2. For  $V > 21$  ( $M_V > +8$ ), the main sequence becomes lost in a general spread of points across the whole diagram. Figure 1 does not represent a “complete” sample, since the limiting magnitudes on our separate frames are not all identical. Nevertheless, the trend for the faint images to scatter toward the blue side of the

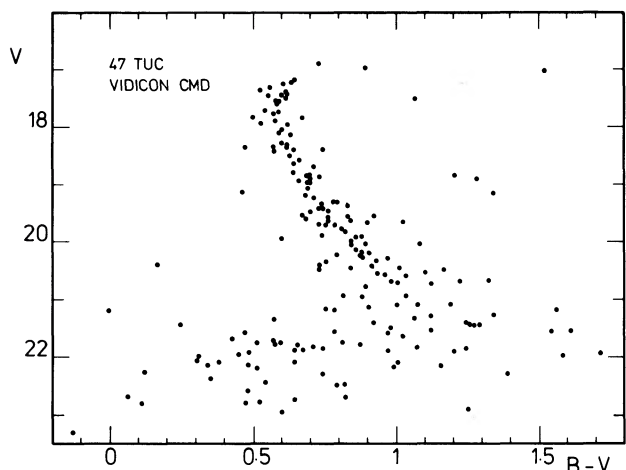


FIG. 1.—The CMD for the main sequence of 47 Tuc, derived from the CTIO SIT vidicon camera and the RICHFLD reduction programs. All detectable images (as selected by eye and reduced with RICHFLD) fainter than  $V = 17$  in the vidicon frames are plotted.

diagram occurs in all frames individually, and the total spread appears too large to arise solely from internal errors (Table 2) or a systematic color error setting in suddenly near  $V \sim 21.5$ . The RICHFLD profile scalings used to fit these images are, however, extremely small and critically dependent on the characteristics of the local sky noise. Future tests with artificial star fields should help specify the true errors of these data with more confidence. If real, the scatter of faint images is most likely due to a combination of (a) foreground stars and distant background galaxy images (we estimate  $\sim 20$  such images would be expected to appear in Fig. 1 for  $21 < V < 23$ ; cf. Harris and Smith 1981) and (b) a population of old SMC field stars at  $M_V \geq +3$  (e.g., Hawkins and Bruck 1982).

3. For  $V < 21$ , our CMD gives a differential luminosity function slope of virtually zero (a rather uniform population of stars along the main sequence). By contrast, Da Costa (1982) finds  $\Delta \log \phi / \Delta m \approx 0.6$  from star counts over the same luminosity range and radial location. Our result is puzzling since it is just at these relatively large distances from the cluster center that the largest proportions of low-mass stars should be seen. Our small sample of stars prohibits any stronger statements at present, but interesting questions concerning the cluster mass function may arise once much larger areas have been surveyed with comparable, thorough photometric calibration.

#### IV. ISOCHRONE FIT AND DISCUSSION

In Figure 2, we have combined our vidicon data for  $V < 21$  with selected stars brighter than  $V = 17.2$  from the survey of Hesser and Hartwick (1977, Fig. 6, Tables 1 and 2). It is encouraging that the vidicon CMD joins

smoothly onto the earlier photographic CMD at the turnoff, without any further scale adjustments. The mean locus for the CMD ( $V \geq 16$  only) is summarized in Table 3.

VandenBerg's (1983) monumental treatment of isochrone fits to all globular clusters with currently available main-sequence photometry treats the effects of the model atmosphere, helium abundance  $Y$ , heavy-element abundance  $Z$ , CNO abundance, and the mixing length ratio  $\alpha$ . In Figure 2, we have superposed the *same* set of isochrones that VandenBerg's exhaustive study found to produce the best match to 47 Tuc ( $Y = 0.2$ ,  $Z = 0.006$ ,  $\alpha = 1.65$ ), with  $E_{B-V} = 0.04$  (Hesser and Hartwick 1977) and a distance modulus  $(m - M)_V = 13.10$ . At all levels through the subgiant-turnoff region, these isochrones accurately match the CMD for an age of  $15\text{--}18 \times 10^9$  yr. The absolute magnitude of the red horizontal branch (at  $V_{HB} = 14.05$ ) is  $M_V(HB) = 0.95$  for this fit, and the bluest part of the main sequence is  $\Delta V(\text{turnoff} - HB) = (3.5 \pm 0.2)$  mag fainter.

Rather than repeat the excellent discussions by VandenBerg (1983) or Janes and Demarque (1983) of the many internal uncertainties in the isochrone fits, we wish simply to emphasize here that the deeper, more precise vidicon CMD is consistent with these earlier

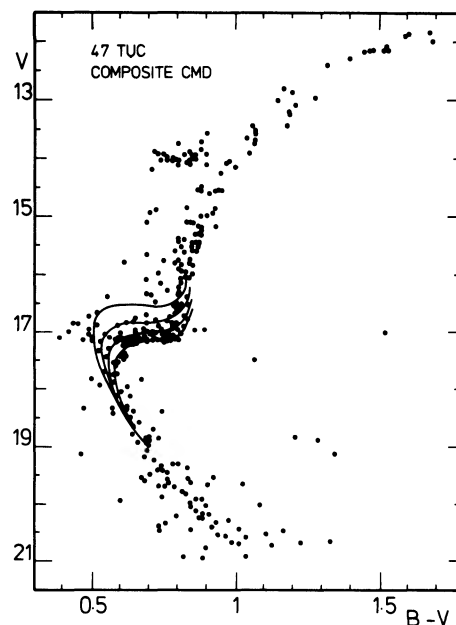


FIG. 2.—Composite CMD for 47 Tuc, including the vidicon data from Fig. 1 ( $V < 21$ ) and bright ( $V \leq 17.2$ ) photographic data from Hesser and Hartwick (1977, Tables 1 and 2). The photographic sample was drawn from measurements over an area of  $\sim 180$  arcmin<sup>2</sup> between  $r = 13'$  and  $20'$ , and so greater numbers of field stars appear in it than in the  $\sim 3.8$  arcmin<sup>2</sup> vidicon sample. The superposed isochrone lines (from VandenBerg 1983) have ages of 9, 12, 15, and 18 billion years, with  $Y = 0.2$ ,  $Z = 0.006$ ,  $\alpha = 1.65$ .

analyses. Furthermore, the consistent tendency seen in many clusters (cf. VandenBerg) for the faintest observed parts of the main sequence to deviate to the red of the isochrones does not appear in our new 47 Tuc CMD. We ascribe the difference of  $\Delta(B - V)(\text{pg} - \text{vidicon}) \sim 0.05$  at  $V \approx 19$  between our study and Hesser and Hartwick's (1977) to small residual errors in calibration near their photographic limit; and we suggest that further use of SIT and CCD imagery may turn up similar systematic problems with other faint photographic surveys (see also Butcher and Oemler 1978). We hope as well that the production of more new CMDs like ours will stimulate development of additional stellar models to cover the fainter parts of the main sequence: the isochrones in Figure 2 stop well short of the *observational* limit, primarily because of the difficulties in fixing and transforming model-atmosphere characteristics for red low-luminosity stars (see VandenBerg 1983).

The isochrone in Figure 2 has  $[\text{Fe}/\text{H}] \approx -0.5$ , which remains noticeably higher than the controversial echelle spectroscopic measurements of  $[\text{Fe}/\text{H}] \approx -0.8$  to  $-1.2$  discussed at length elsewhere (Cohen 1980, 1983; Dickens, Bell, and Gustaffson 1978; Pilachowski, Canterna, and Wallerstein 1980; Bell 1981; Bell and Gustaffson 1982; Pilachowski, Sneden, and Wallerstein 1983). However, plausible uncertainties in the isochrone ( $T_e$ ,  $M_{\text{bol}}$ ) conversions and in the adopted distance modulus are still large enough that no major concern over this Z-difference may yet be called for.

The typical ages of  $(15-18) \times 10^9$  yr which represent the best current results for the galactic globular clusters are now well known to be in plain disagreement with those currently proposed measurements of the Hubble constant yielding  $H_0 \approx 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$  (Sandage 1982; VandenBerg 1983; Janes and Demarque 1983). (Curiously, the globular clusters themselves have been used as "standard candles" [with the *same* fundamental RR Lyrae distance scale that enters the age determina-

TABLE 3  
MEAN LINE FOR THE MAIN-SEQUENCE CMD

$V$	$B - V$	$V$	$B - V$
16.00 ...	0.83	17.50 ...	0.58
16.50 ...	0.805	17.70 ...	0.58
17.00 ...	0.79	18.00 ...	0.59
17.10 ...	0.70	19.00 ...	0.69
17.20 ...	0.62	20.00 ...	0.85
17.30 ...	0.60	21.00 ...	1.06

tion process] to calibrate extragalactic distances, with well-documented results that directly support the "high"  $H_0 \approx 100$  values [Hanes 1979; Harris and Racine 1979; Mould, Aaronson, and Huchra 1980].) Rather than promoting one view or the other, we believe that this discrepancy represents a legitimate scientific problem in the sense that neither of these major procedures (cluster age calibration versus extragalactic distance scale) can clearly be branded as erroneous within its own framework. Both are based on well-scrutinized chains of reasoning, and it is likely that any resolution of their detailed differences will require much additional understanding in both observational and theoretical directions.

We are grateful for invaluable advice and instruction given by J. V. Barnes, S. Hammond, and L. Stryker during the RICHFLD analysis; for the hospitality of B. and R. Aguirre, J. and R. Barnes, and B. and R. Gayoso at several periods during the data reductions; and for helpful comments on the manuscript by A. Sandage. We wish also to thank the staff of the Royal Observatory, Edinburgh, for their hospitality while this *Letter* was drafted, and the directors and staffs of both CTIO and KPNO. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada through research grants to W. E. H.

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BRUCE ATWOOD: Cerro Tololo Inter-American Observatory, Casilla 603, La Serena, Chile

WILLIAM E. HARRIS: Department of Physics, McMaster University, Hamilton, Ontario L8S 4M1, Canada

JAMES E. HESSER: Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, 5071 West Saanich Road, Victoria, B. C. V8X 4M6, Canada