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AN ADDITIONAL CONSTRAINT ON THE EARLY EVOLUTION OF THE GALAXY FROM NEW OBSERVATIONS OF 47 TUCANAE

F. D. A. HARTWICK*
University of Victoria

AND

JAMES E. HESSER
Observatorio Interamericano de Cerro Tololo†
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ABSTRACT

Photoelectric observations of 100 stars in the globular cluster 47 Tucanae have been obtained at Cerro Tololo; when combined with recent work by Cannon and Menzies, a composite photoelectric color-magnitude diagram of 180 stars, 40 of which lie on or below the turn-off, can be constructed. From it and a photographic-luminosity function obtained from ~1500 stars we estimate: $E(B - V) = 0.04$, $[\mathrm{Fe/H}] = -0.48$, $(m - M)_0 = 13.03$, $10.3 \lesssim$ age $\lesssim 13.7 \times 10^9$ yrs, and $Y \sim 0.23$; these results are consistent with the Eggen, Lynden-Bell and Sandage collapse picture of the formation of the halo of our Galaxy.

Subject headings: abundances, stellar — galactic structure — globular clusters — photometry — population II stars — stellar evolution

I. INTRODUCTION

Eggen, Lynden-Bell, and Sandage (1962) (ELS) have presented evidence from an analysis of the motions of old stars that the Galaxy collapsed in a time of the order of $\sim 2 \times 10^8$ years. In his discussion of the C-M diagrams of the metal-deficient halo globular clusters, Sandage (1970) found that the observed spread in age was consistent with the ELS model. Recent models by Larson (1969, 1974) show that depending on the initial conditions the collapse of a spherical galaxy can take place on time scales much longer than $\sim 2 \times 10^8$ years. Because most conventional models of galaxy evolution predict that heavy-element abundances increase with time, an important constraint on collapsing models of our own Galaxy can be made by determining the ages of the metal-rich globular clusters.

Because of its near normal metallicity, high galactic latitude, low reddening, and proximity, 47 Tucanae is unique among the metal-enriched Population II clusters. Using existing photographic data (Tifft 1963), Hartwick and Vanden Berg (1973) found, assuming $Y = 0.3$, an age of 7.3×10^9 years. This age is considerably lower than that found by Sandage (1970) for several halo clusters assuming a similar value of the helium abundance, and is inconsistent with the collapse model of ELS. Recently, however, Cannon (1974) and Menzies (1973) have indicated the existence of systematic errors in the bright end of the existing photometry. A major reinvestigation of 47 Tucanae to fainter magnitudes at Cerro Tololo Inter-American Observatory allows us to attempt clarification of the situation.

* Visiting Astronomer, Cerro Tololo Inter-American Observatory.

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II. OBSERVATIONAL DATA

A new photoelectric sequence consisting of ~100 stars ($8.5 \lesssim V \lesssim 19.2$ mag) was observed in the western and southern portions of 47 Tucanae during the 1972 and 1973 seasons at CTIO with the 91-cm and 1.5-m telescopes. Observing techniques were those described elsewhere (Hartwick and Hesser 1972; Hartwick, Hesser, and McClure 1972), except that the majority of the data discussed herein were obtained with a dual-channel (B, V) photometer with S20 photocells rather than with a single-channel 1P21 instrument.

Superposition of the resultant photoelectric C-M diagram, figure 1*a*, with Tifft's (1963) classical photographic version, indicates that the ~0.08 mag systematic difference in $(B - V)$ color found along the giant and subgiant branches of the 47 Tucanae C-M diagram by Menzies (1973) and Cannon (1974) persists to the main-sequence;[1] as suggested by the other investigators, the difference probably stems from the photographic transfers made in the early work. Intercomparison by superposition of the giant and horizontal branches of 47 Tucanae obtained in recent studies reveals some small systematic differences (table 1). When viewed as a function of increasing radial distance from the cluster center, the differences of table 1 are found to be in a sense opposite to that of the integrated photometry of Gascoigne and Burr (1956) and Freeman and Chun (1973). Crowding and background problems at the radial distances of $r \sim 6'$ may account for some, if not all, of the effects observed in table 1. We also note that the excellent color agreement between the three photoelectric investigations at larger radius, where crowding

[1] Dr. Cannon has kindly provided us with some unpublished photometry extending to the turnoff, and the agreement between his results and ours is excellent, as can be seen in fig. 1*b*.

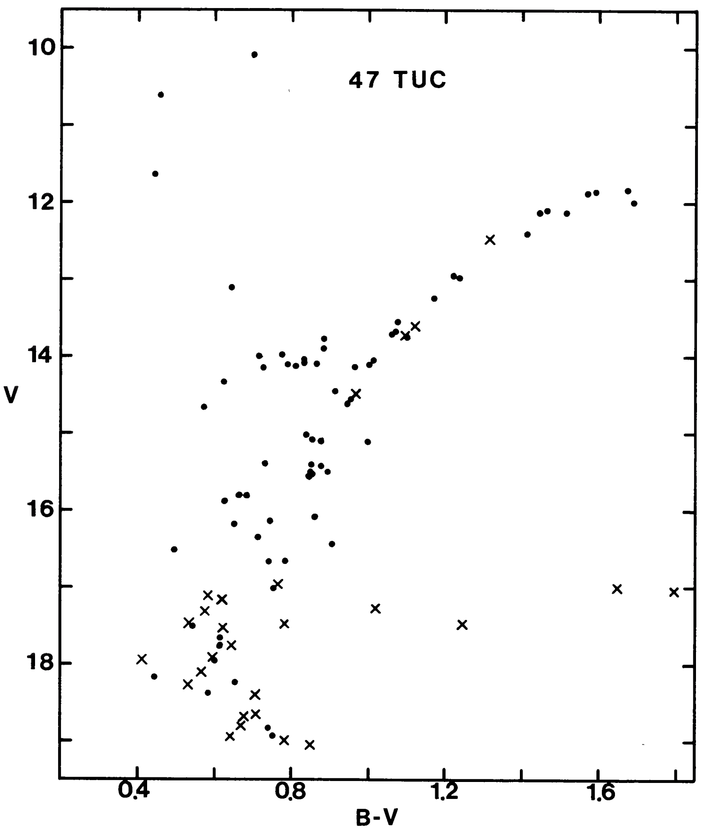

FIG. 1*a*.—The photoelectric sequence stars measured at CTIO that have been used for the reduction of the photographic data of fig. 2. Dots represent stars observed on more than one night, while crosses represent stars observed on only one night. Of the CTIO sequence stars, 75% have more than one observation.

TABLE 1

COMPARISON OF PHOTOMETRIC INVESTIGATIONS OF 47 TUCANAE*

Author	$\sim\langle r \rangle$	ΔV (mag)	$\Delta(B-V)$ (mag)
This work..............	17.′3	0.00	0.00
Cannon 1974...........	13.9	0.00	0.00
Cathey 1973............	6.0	−0.10	−0.05
Eggen 1972.............	6.0	−0.05	−0.04
Menzies 1973...........	17.5	−0.04	0.00
Tifft 1963..............	14.8	0.00	−0.08

* All investigations but Tifft's are photoelectric; $\langle r \rangle$ is the approximate radial distance of the measured stars from the cluster center, and negative differences for ΔV and $\Delta(B-V)$ mean that the measures are fainter and bluer than the values found in this work.

and background effects are expected to be much less severe, sets stringent limits on the existence of differential reddening over the wide area at $r \sim 16'$ sampled in these investigations.

From the investigations of Cannon, Menzies, and ourselves, a *photoelectric* C-M diagram for 180 nonredundant stars has been constructed (fig. 1*b*). The striking features of this diagram are borne out by photographic photometry of more than 1500 stars (fig. 2), namely: lack of strong differential reddening effects on the cluster periphery; a giant branch of little intrinsic width; a stubby, red, well-defined horizontal branch; and a subgiant branch with a well-defined red edge but an ill-defined blue edge. For completeness we note that no stars have been eliminated from the diagrams on the basis of being suspected Galactic or SMC field stars.

III. PROVISIONAL ESTIMATES OF E_{B-V}, [Fe/H], $(m-M)_0$, AND AGE

We have used four methods to estimate the foreground reddening. (1) Crawford and Barnes (private communication) find from *uvby*–Hβ photometry of five foreground early-type stars that $E_{(B-V)} = 0.037 \pm 0.019$. (2) *UBV* photometry (Blanco *et al.* 1968) of five foreground stars within $\sim 6°$ of the cluster indicates that $E_{(B-V)} = 0.00 \pm 0.02$ mag. (3) The revised cosecant law (Sandage 1973) yields $E_{(B-V)} = 0.05$. (4) From a spectroscopic investigation of proven SMC foreground stars, Feast, Thackeray, and Wesselink (1959) found E_{B-V}(SMC) = 0.04–0.07. An unweighted mean of the above determinations yields our adopted value of 0.04 mag for the reddening in front of 47 Tucanae. (We also

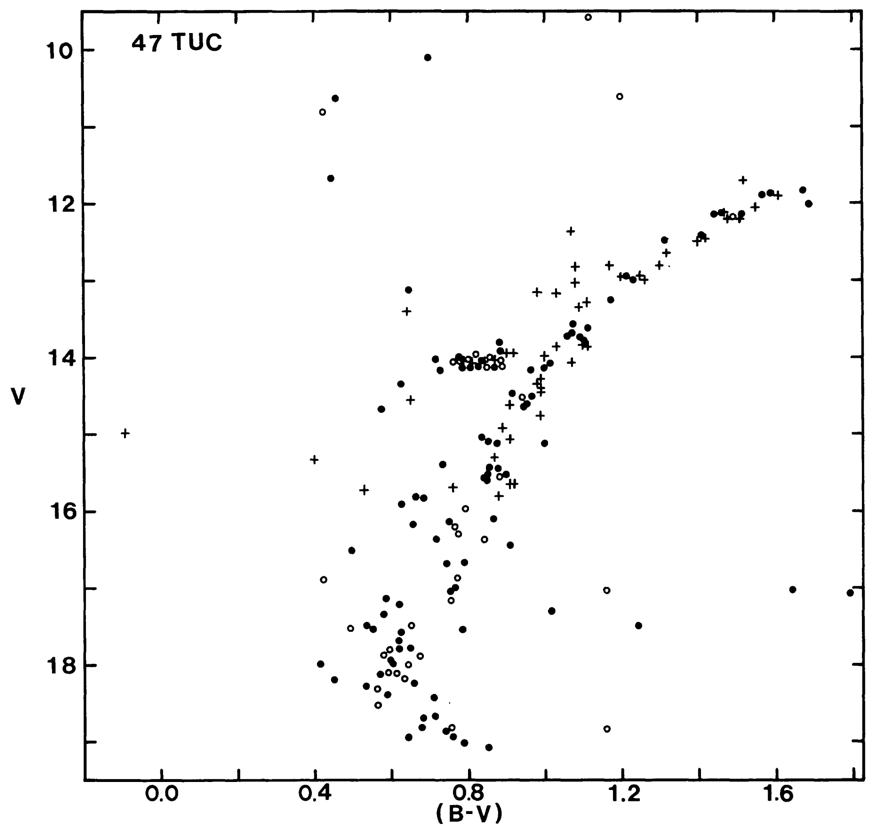

FIG. 1*b*.—The photoelectric data for ~180 nonredundant 47 Tucanae stars from the investigations of Cannon (*open circles*), Menzies (*crosses*), and this paper (*filled circles*). Menzies's data have been adjusted by an amount equal to the small ΔV value of table 1.

note that the interstellar polarization measures of Mathewson and Ford [1970] are consistent with this value.)

UBV photometry of a large number of 47 Tucanae giants by Menzies (1973), as augmented by the CTIO data, can be used to estimate $\delta(U-B)_{B-V=1.0}$, which, from the relation of Wallerstein and Helfer (1966), gives $[\mathrm{Fe/H}]_{47\ \mathrm{Tuc}} = -0.6$ with respect to the Hyades, a value consistent with the results of Feast and Thackeray (1960) and McClure and Osborn (1974). We adopt $[\mathrm{Fe/H}] = -0.48$ with respect to the Sun for 47 Tucanae.

The procedure to determine the distance modulus is based on work by Sandage (1970). From our adopted [Fe/H] we find $\delta(U-B) = 0.11$ for the dwarfs via the relation of Wallerstein (1962). From figure 16 of Sandage (1970) we find a $\Delta M_V = 0.37$ between the fiducial main sequence and that of the field stars with the same ultraviolet excess as the 47 Tucanae stars. From our figure 1*b* and our adopted reddening we find $(m-M)_0 = 13.03 \pm 0.20$ and $V_{\mathrm{T.O.}} = 17.5 \pm 0.2$ so that $M_{V,\mathrm{T.O.}} = 4.34 \pm 0.28$ mag or $M_{\mathrm{bol\ T.O.}} \simeq 4.23$ mag. M_V of the horizontal branch assumes the relatively faint value of $\sim +1.0$ mag. It is worth emphasizing that because of the slope of the unevolved main sequence in the $(M_V, B-V)$-plane, $\Delta M_V \simeq 6.0\,\Delta(B-V)$, that small errors in the observed colors due either to systematic errors in the photometry or the reddening estimate will lead to correspondingly larger errors in $(m-M)$, and hence t_9.

Using equation (1) of Hartwick and Vanden Berg (1973) with $Z_{47\ \mathrm{Tuc}} = 0.006$, we find ages, $t_9 = 10.3$ or 13.7 years for $Y = 0.3$ and 0.2, respectively, that bracket the ages of the halo clusters, $\sim 11.5 \times 10^9$ years (Sandage 1970). (We are currently reinvestigating the age determination of M71 [Hartwick and Vanden Berg 1973], but we feel that no firm conclusion will be drawn until an accurate reddening estimate for M71 is obtained.)

Finally, as figure 2 also represents the luminosity function of the cluster, a qualitative estimate of the He abundance can be made by comparison of the observed function with theoretically determined ones for a variety of He abundances. Since theoretical functions are not yet available for $Z > 10^{-3}$, we have compared our observations with the results of Simoda and Iben (1970) for $Z = 10^{-3}$; the steepness of the function just beyond the turnoff is consistent with $Y = 0.23 \pm 0.10$.

IV. CONCLUSIONS

From analysis of the new data reported herein, and utilizing the most recent work of other observatories, we have derived an age by main-sequence fitting for the metal-rich globular cluster 47 Tucanae. Within the uncertainties, the age of 47 Tucanae is indistinguishable

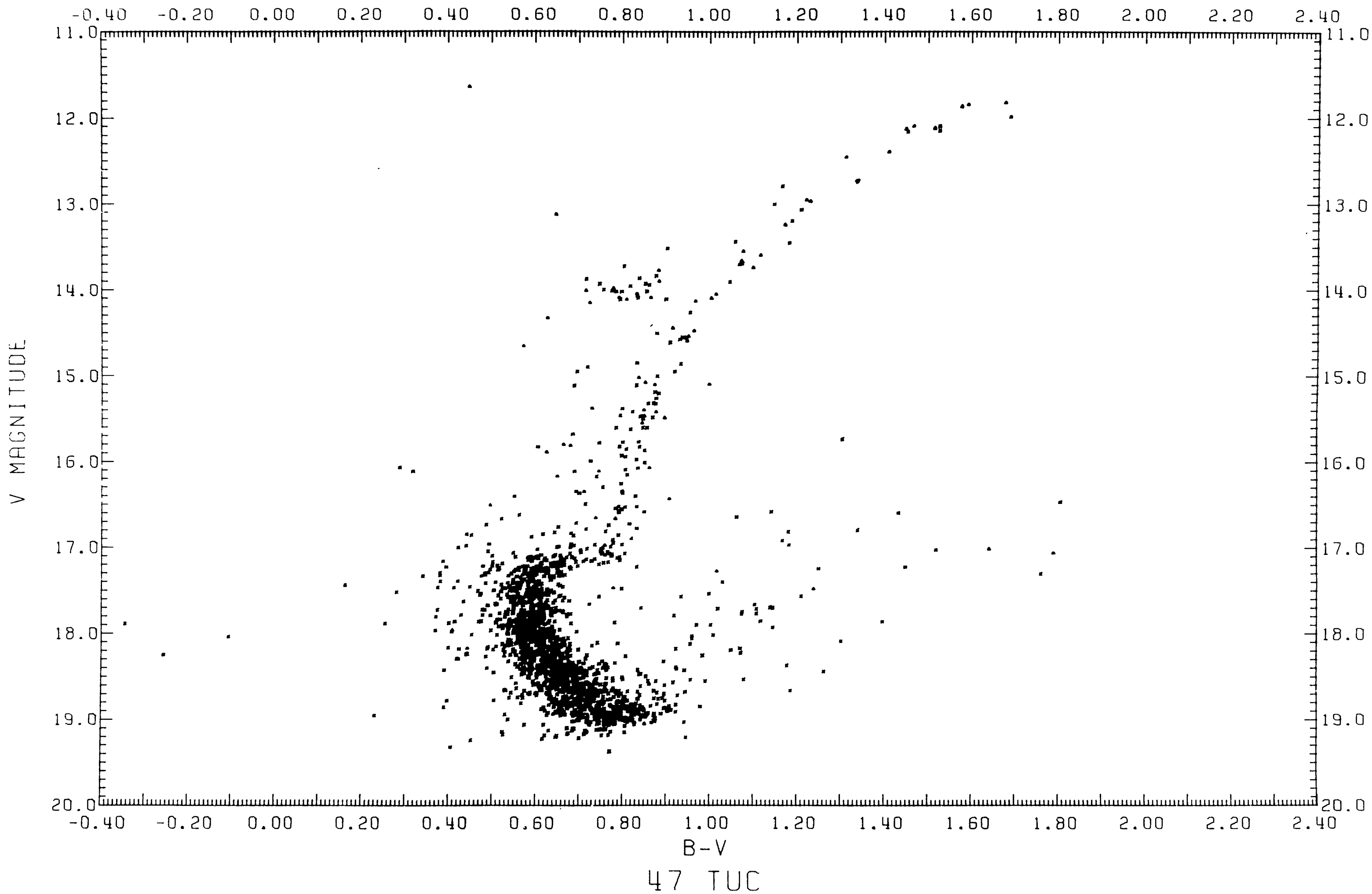

FIG. 2.—The photographic C-M diagram and luminosity function for ~1500 stars measured on three 103aD+GG 14 (*V*) plates and three 103aO+GG13 (*B*) plates; the crosses are the photographic observations, while the triangles are the photoelectric sequence stars measured in this work.

from the ages of the metal-poor clusters studied by Sandage (1970), indicating that its age and chemical composition are consistent with the ELS collapse model for the Galaxy. Evaluation of the accuracy of this new constraint on the chemical evolution of the Galaxy during the epoch of globular-cluster formation should benefit greatly from precise age and composition determinations for other metal-rich globular clusters.

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F. D. A. Hartwick: Dept. of Physics and Astronomy, University of Victoria, Victoria, B.C., Canada

James E. Hesser: AURA, Inc., Casilla 63-D, La Serena, Chile