STELLAR POPULATIONS IN THE DWARF ELLIPTICAL GALAXY NGC 147¹

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ABSTRACT

Deep *V* and *I* CCD images in a central and an outer field of the Local Group dwarf elliptical galaxy NGC 147 have been obtained with the Wide Field and Planetary Camera-2 (WFPC2) on board of the Hubble Space Telescope. The color-magnitude diagram shows a number of interesting features, including a well defined red giant branch (RGB), a red horizontal branch (HB), a strong red clump, and a small number of extended asymptotic giant branch (EAGB) stars. A mean distance modulus of $(m - M)_0 = 24.39$ is derived based on both the HB and the RGB tip brightness. The metallicity $[Fe/H]$ as determined from the RGB color has a mean value of -0.91 in the central field, and -1.0 in the outer field; and the outer field shows a weak tendency of increasing metallicity with galactocentric radius. A metallicity dispersion is also present in the galaxy, and it shows a clear radial variation in the sense that a larger dispersion is seen at smaller radii. The small population of EAGB stars indicates the presence of intermediate-aged (several Gyr) stars in the galaxy, while the absence of the main sequence stars with $M_V < 1$ shows that star formation ceased at least 1 Gyr ago. The distribution of the EAGB stars indicates that the younger stars are more centrally concentrated than the majority of older stars. A similar age gradient is also implied by the relative distribution of the HB stars, which appear to be more populous at larger radii. These results are considered within the context of theoretical models for the evolution of dwarf elliptical galaxies. © 1997 American Astronomical Society. [S0004-6256(97)02003-7]

1. INTRODUCTION

Dwarf elliptical galaxies are among the most numerous galactic systems in the universe. Over the past decade or so, these objects have been extensively investigated, both theoretically and observationally by many investigators (see Ferguson & Binggeli 1994, Gallagher & Wyse 1994 for recent reviews). The study of stellar populations provides a unique way for us to understand the star formation history and hence the evolution of these systems and the universe at large. Due to the low luminosities and small sizes of these systems, however, detailed stellar population studies extending to older stars are only possible for the nearby galaxies, prima-

rily in the Local Group (LG). While most of the LG galaxies have previously been carefully studied using ground-based instruments, the superb imaging quality of the *Hubble Space Telescope* (*HST*) allows us to re-examine the stellar populations of the LG galaxies in much more detail and to a significantly deeper level. In this paper, we present our study of the dwarf elliptical galaxy NGC 147 based on *HST* observations, which is part of a continued program by the WFPC2 instrument definition team to study the stellar populations in a number of LG galaxies. The other galaxy we have studied in this series is the Large Magellanic Cloud (LMC) (Gallagher *et al.* 1996).

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FIG. 1. A 15×15 arcmin square field of NGC 147, taken from the archives of the STScI Digitized Sky Survey. The WFPC2 FOVs of our two fields are shown.

NGC 147 is one of the three well known dwarf elliptical companions to the giant spiral M31. As compared to the other two companions (NGC 185, NGC 205), as well as to most of the companion dwarfs to our own Galaxy, NGC 147 has long been recognized to be special in terms of stellar content. For example, early studies have revealed that both NGC 185 and NGC 205 contain dust clouds and centrally concentrated blue stars (Hodge 1963; Hodge 1973; Gallagher & Hunter 1981), but no evidence was found for these Pop I indicators in NGC 147 (Hodge 1976). Moreover, NGC 185 and NGC 205 all contain intermediate-age populations (Richer *et al.* 1984; Davidge 1992; Lee *et al.* 1993); on the other hand, the study of deep ground-based CCD images in an outer field of NGC 147 by Mould *et al.* (1983) detected no stars younger than 12 Gyr. However, Davidge (1994) recently reported the discovery of a few moderately bright as-

TABLE 1. Observation log.

Rootname	Filter	Exposure	Field	Date
u2ob0201p	F555W	600	inner	24MAY95
u2ob0202p	F555W	500	inner	24MAY95
u2ob0203p	F814W	400	inner	24MAY95
u2ob0204p	F814W	400	inner	24MAY95
u2ob0101t	F555W	2400	outer	21JUN95
u2ob0102t	F555W	1300	outer	21JUN95
u2ob0103t	F555W	1300	outer	21JUN95
u2ob0104t	F555W	1300	outer	21JUN95
u2ob0105t	F555W	1300	outer	21JUN95
u2ob0106t	F555W	2800	outer	21JUN95
u2ob0107t	F555W	2800	outer	21JUN95
u2ob0108t	F814W	1300	outer	21JUN95
u2ob0109t	F814W	1300	outer	21JUN95
u2ob010at	F814W	1300	outer	21JUN95
u2ob010bt	F814W	1300	outer	21JUN95
u2ob010ct	F814W	1300	outer	21JUN95
u2ob010dt	F814W	1300	outer	21JUN95

TABLE 2(a). NGC 147—inner field photometry.*

ID	X ^a	Y ^a	V ₀	σ _V	I ₀	σ _I
(a)						
1	800.99	1021.15	25.270	0.339	24.717	0.552
2	800.97	889.63	26.247	0.724	24.482	0.450
3	800.83	978.08	26.965	0.630	24.206	0.316
⋮	⋮	⋮	⋮	⋮	⋮	⋮

*The coordinate system is defined by simply stacking up the *contiguous* fields of the 4 chips in each field (see *HST*/WFPC2 Handbook v3.0), and defining the central joining point to be at (800,800). *X* and *Y* are in units of WF pixels.

*Tables 2(a) and 2(b) can be found in the AAS CD-ROM Series, Vol. 8, 1997. Only the first page is shown here for form and content.

TABLE 2(b). NGC 147—outer field photometry.

ID	X ^a	Y ^a	V ₀	σ _V	I ₀	σ _I
(b)						
1	800.78	850.89	25.998	0.148	25.203	0.390
2	798.63	1022.03	26.033	0.168	25.224	0.166
3	798.57	853.44	25.780	0.104	24.861	0.125
⋮	⋮	⋮	⋮	⋮	⋮	⋮

*See footnote to Table 2(a).

ymptotic giant branch stars in the central region of NGC 147, indicating that an intermediate-age population is present, at least in the nuclear region.

We have obtained deep F555W(*V*) and F814W(*I*) images in two fields of NGC 147 with the *HST*. These high quality images reveal the stellar population of this galaxy in unprecedented detail. In Sec. 2 below, we describe our observations and data reduction. We present our analyses of the stellar populations in the galaxy in Secs. 3, 4, and 5. Finally, in Sec. 6, we conclude with a summary of our study.

2. OBSERVATIONS AND DATA REDUCTION

Two fields were selected for our study of NGC 147, one in the central region centered at the globular cluster Hodge #1, and the other in an outer region centered at another globular cluster, Hodge #3, which is some 4 arcminutes south of the galaxy center. Figure 1 shows the locations of these two pointings. Deep F555W and F814W images were obtained with the WFPC2 on 1995 May 24 for the central region, and on 1995 June 21 for the outer region. Table 1 presents the observation log. The images were calibrated following the procedure of Holtzman *et al.* (1995) using the bias and dark frames obtained close to the dates of our observations. Figures 2 and 3 (Plates 31 and 32) show mosaics of the F555W images of the central and outer fields, respectively. No obvious dark clouds or star clusters other than the known Hodge clusters are apparent in either field.

Stellar photometry was carried out with the new DAOPHOT-II/ALLFRAME software (Stetson 1994a), using quadratically varying Point Spread Functions (PSF) derived by Stetson based on WFPC2 images of NGC 2419 and Pal 4 obtained at the −88 degree CCD temperature. The methodology of PSF construction for WFPC2 image data was described in Stetson (1994b, 1994c). Since ALLFRAME processes all the images in a given field simultaneously, it is

FIG. 4. The V_0 vs $(V-I)_0$ and I_0 vs $(V-I)_0$ diagrams for the 78,421 stars in the inner field. The magnitudes and colors were corrected for Galactic extinction as described in text. The relative distribution of the stars is illustrated by the number density contours, which are drawn at levels of (5, 10, 20, 50, 100, 200, 300, 500, 700) stars per $1/80 \times 80$ of the window area. Also overlotted are the RGB curves of Galactic globular clusters, M15 and 47 Tuc.

FIG. 5. The V_0 vs $(V-I)_0$ and I_0 vs $(V-I)_0$ diagrams for the 38,203 stars in the outer field. The magnitudes and colors were corrected for Galactic extinction as described in text. The relative distribution of the stars is illustrated by the number density contours, which are drawn at levels of (5, 10, 20, 50, 100, 200, 300, 600, 900) stars per $1/80 \times 80$ of the window area. Also overlotted are the RGB curves of Galactic globular clusters, M15 and 47 Tuc.

able to reject cosmic-ray events and other random hot pixels. The output from ALLFRAME is a list of photometry files, one for each image. These files were then combined to produce a single photometry file for each detector that lists all the raw F555W and F814W magnitudes for all the stars and filters. The total number of stellar objects is 78,421 in the inner field, and 38,203 in the outer field. These raw magnitudes were further processed by correcting for exposure time and geometric distortion effects (Holtzman *et al.* 1995), and then weight-averaged to give a final optimal estimate of the raw magnitude for each star in each filter.

The final magnitudes were converted to standard Cousins V and I magnitudes using the photometric coefficients of Holtzman *et al.* (1995) and the aperture corrections derived by Stetson for the DAOPHOT PSF-fitting magnitudes. Since our images were taken at the cooler CCD temperature, and there is moderate background in the fields, we made no corrections for the effect of charge transfer efficiency. Another photometric anomaly with the WFPC2, originally discovered by P. B. Stetson, is the so-called long versus short exposure time problem, which appears to make a star observed in short exposures (~ 200 s) fainter than observed in long exposures (~ 1000 s) by approximately 0.05 mag (more details about this phenomenon may be found at http://www.stsci.edu/ftp/instrument_news/WFPC2/Wfpc2_cte/ctetop.html). Since Holtzman's photometric zero-points were based on short exposures, we also corrected for this effect for both our inner field (400–500 s) and outer field data (1300–2800 s).

The reliability of our ALLFRAME photometry and calibration were independently checked by Saha (1996, private communication) using his DoPHOT stellar photometry pack-

age, the two sets of photometry agree with each other to within 0.02 mag.

Finally, we applied a correction for Galactic extinction of $A(V_0)=0.576$ and $A(I_0)=0.365$, adopting a value of 0.18 for $E(B-V)$ (Burstein & Heiles 1984), $R_V=3.2$, and an extinction law by Cardelli *et al.* (1989). We use V_0 , I_0 , and $(V-I)_0$ to indicate extinction-corrected magnitudes and colors in the following sections.

Our complete photometry data will be published on the AAS CDROM as two ASCII tables, Tables 2(a) and 2(b), for the inner and outer fields, respectively. The first 3 entries of each table are shown below. A running number is given in the first column of each table. The coordinates of the stars are listed in the second and third columns, while the calibrated magnitudes and magnitude errors are given in the last four columns.

3. THE COLOR-MAGNITUDE DIAGRAMS

3.1 Field Stars

The $V_0-(V-I)_0$ and $I_0-(V-I)_0$ diagrams for the inner and outer fields are shown in Figs. 4 and 5, respectively. In order to better illustrate the relative distribution of the stars in the CMD, the number density contour maps of the star distributions are overlaid on the diagrams. The number density was constructed by dividing the window of the color-magnitude diagram into 80×80 grids; the contour levels were defined to be (5, 10, 20, 50, 100, 200, 300, 500, 700) stars per grid-area for the inner field, and (5, 10, 20, 50, 100, 200, 300, 600, 900) stars per grid-area for the outer field. Also overlotted in the figures are the red giant branch (RGB) loci of the Galactic globular cluster M15 ($[Fe/H]=$

FIG. 6. The color-magnitude diagrams of the stars in the regions of the three globular clusters in NGC 147, Hodge 1, Hodge 2, and Hodge 3. All the detected stars within, respectively, 5, 5, and 6 arcseconds of the center of each cluster are shown. Stars within 2 arcseconds of the center of each cluster are plotted as filled dots. The RGB loci of Galactic globular clusters, M15 ($[\text{Fe}/\text{H}] = -2.17$) and 47 Tuc ($[\text{Fe}/\text{H}] = -0.71$) are overplotted.

-2.17) and 47 Tuc ($[\text{Fe}/\text{H}] = -0.71$), taken from Da Costa & Armandroff (1990). A distance modulus of 24.39 for NGC 147 (see Sec. 4 below) was used to scale the cluster RGBs.

Several interesting features are immediately evident in the CMDs:

(1) Both fields show a well-defined RGB; the inner-field RGB is much broader than that in the outer field.

(2) A well-defined (red) horizontal branch (HB) is present in the outer field, but no HB stars are clearly distinguishable in the inner field. This result is mainly due to the fact that the inner field was less exposed by more than 1 mag than the outer field. The crowding in the inner field may also play a role.

(3) Both fields show a strong clump on the RGB. These stars are centered at the $(V-I)_0 = 0.90$, $I_0 = 24.05$ in the inner field, and $(V-I)_0 = 0.95$, $I_0 = 24.12$ in the outer field.

(4) The extended AGB stars above the tip of the RGB are clearly present in both fields, and the fraction of EAGB stars appears larger in the inner field than in the outer field.

(5) No main sequence stars are reliably detected, indicating that the main sequence turnoff level is at least ~ 1.5 mag below the HB level.

Some of the outliers in the color-magnitude diagrams (Figs. 4 and 5) are foreground stars in our Galaxy. The Galactic star count model of Ratnatunga & Bahcall (1985) predicts about 100 foreground stars with $V < 27$ in each of our fields, which is a tiny fraction of the total number of stars detected above the same magnitude limit. The contamination rate is somewhat higher in the EAGB region. We detected a total number of 405 and 136 stars with $I_0 < 20.3$ and $V_0 > 19$ in the inner field and outer field respectively; the model predicts some 15 foreground stars in the visual magnitude range from 19 to 22. This corresponds to a predicted contamination rate in the EAGB region of about 4% in the inner field and 11% in the outer field, which is not enough to significantly affect our analysis about the EAGB stars in this paper. As a matter of fact, the actual contamination in the EAGB region, for the outer field in particular, might be smaller than the

FIG. 7. Distribution of V_0 magnitude for some 700 stars near the HB in the outer field. The mean HB level is $V_{\text{HB}} = 25.09 \pm 0.02$, which is estimated by weight-averaging with a 2.5σ rejection.

model prediction, judging from the morphology of the EAGB region in the CMD, and also the spatial distribution of these stars in the field, which show a stronger central concentration than other stars.

3.2 Globular Cluster Stars

Three of the 4 known globular clusters in NGC 147, Hodge 1, Hodge 2, and Hodge 3, lie within our field of view. The CMDs of these clusters are presented in Fig. 6. Stars were selected within radii of 5, 5, and 6 arcseconds from the three clusters, respectively. The filled dots represent stars within 2 arcseconds of the central region of each cluster, the open circles are the stars in the outer region of each cluster. The RGB loci of the Galactic globular clusters M15 ($[\text{Fe}/\text{H}] = -2.17$) and 47 Tuc ($[\text{Fe}/\text{H}] = -0.71$) are also overlaid in the figure.

It is apparent that the overall CMD morphologies of these clusters are quite different from that defined by the majority of the field stars shown in Figs. 4 and 5. The most striking difference is that the clusters, especially Hodge 1 and Hodge 3, contain more blue RGB stars, and these blue stars are predominantly concentrated toward the centers of the clusters. The phenomenon that the globular clusters have bluer color than the field stars (at the same radii) in their host galaxy has previously been reported for a number of other galaxies (e.g., Strom *et al.* 1981; Cohen 1988.) This phenomenon is consistent with the idea that the globular clusters are older and more metal poor than the field stars in a galaxy (e.g., Fall & Rees 1985). The spectroscopic study of the Hodge 1 and 3 clusters in NGC 147 by Da Costa & Mould (1988) showed that the metallicities of the two clusters are $[\text{Fe}/\text{H}] = -1.9 \pm 0.15$ and -2.5 ± 0.25 , respectively. These results are in good general agreement with the CMDs as shown in Fig. 6. Note that the RGB locus of the Galactic cluster M15 at $[\text{Fe}/\text{H}] = -2.17$ is the left curve in each panel. A cautionary note: stellar photometry for the stars in the cluster regions is probably less reliable than in the field due to the increased crowding.

FIG. 8. The I_0 luminosity function for stars near the RGB tip, in both the inner field (top) and the outer field (bottom). The RGB is identified at $I_0=20.3$ in both fields.

4. DISTANCE AND METALLICITY

A clear detection of both the HB and a well-developed RGB tip in our deep photometry data allows us to determine the distance of NGC 147 more reliably than has been possible using ground-based data. The absolute levels of the HB and the RGB tip (TRGB) are dependent on metallicity, which can be estimated using the empirical color-metallicity relation derived by Da Costa & Armandroff (1990) for metal-poor Galactic globular clusters: $[\text{Fe}/\text{H}] = -15.16 + 17.0(V-I)_{0,-3} - 4.9[(V-I)_{0,-3}]^2$, where $(V-I)_{0,-3}$ is the giant branch color at absolute magnitude $M_I = -3$. We will evaluate $(V-I)_{0,-3}$ as the median color of the stars in absolute I_0 magnitude range $-3.1 < M_I < -2.9$. In order to use this relation, we also need to know the distance of the galaxy (to calculate M_I .) Below we derive distance and metallicity iteratively in a self-consistent manner.

In advance of this discussion it is important to consider some facts which can complicate the interpretation of these CMDs. In particular, the presence of a populous “red clump” indicates that stars will be making a second ascent of the RGB as a part of their AGB evolution. For example, the low metallicity, intermediate age models of Lattanzio (1991) spend roughly equal times at luminosities above the red clump during their first and second RGB ascents for a low metallicity $1.5 M_\odot$ model. Thus what we see as an “RGB” in a galaxy like NGC 147 is actually a mixture of stars of varying ages, metallicities and evolutionary phases. Therefore properties which we derive below from properties of the RGB are necessarily approximate; accurate results will require a full stellar population model that is beyond the scope of this paper.

4.1 Distance and Metallicity Based on HB Stars

To determine distance from the HB of the outer field, we adopt the theoretical luminosity-metallicity relation of RR Lyrae stars given by Lee *et al.* (1990), $M_V = 0.17[\text{Fe}/\text{H}] + 0.82$. The extinction-corrected V_0 magnitude of the HB level was found to be 25.09 ± 0.02 mag; this was determined by weight-averaging with a 2.5 sigma rejection of the stars with $0 < (V-I)_0 < 0.5$ and $24.5 < V_0 < 25.5$. The V_0 magni-

TABLE 3. Determination of distance and metallicity for NGC 147.

Method	Field	$(m-M)_0$	$[\text{Fe}/\text{H}]$
HB	outer	24.44 ± 0.04	-1.04 ± 0.03
TRGB	outer	24.37 ± 0.06	-1.00 ± 0.03
TRGB	inner	24.36 ± 0.06	-0.91 ± 0.03
Mean		24.39 ± 0.05	

tude distribution of these stars is shown in Fig. 7. From our adopted calibration relations, we can now solve for both distance and metallicity by iteration. Since this is a well-defined, nearly-linear problem, the solution is unique and stable, convergence can be quickly achieved even with a very bad initial input. The resultant distance modulus and metallicity are, respectively, $(m-M)_0 = 24.44 \pm 0.04$ and $[\text{Fe}/\text{H}] = -1.04 \pm 0.03$. Note that the errors reflect statistical and photometric uncertainties only. The accuracy of our adopted calibration relations are not very well understood and will be discussed further below.

4.2 Distance and Metallicity Based on TRGB

The I_0 magnitude of the TRGB can also be used as a distance indicator, at least for metal-poor Pop II stellar systems (Costa & Armandroff 1990; Lee *et al.* 1993). The distance modulus is given by $(m-M)_0 = I_0^{\text{TRGB}} + BC_I - M_{\text{bol}}^{\text{TRGB}}$, where $BC_I = 0.881 - 0.243(V-I)_0^{\text{TRGB}}$ is the bolometric correction to I_0 magnitude, and $M_{\text{bol}}^{\text{TRGB}} = -0.19[\text{Fe}/\text{H}] - 3.81$ is the bolometric magnitude on the same distance scale defined by the luminosity-metallicity relation we adopted above in deriving the HB level (Da Costa & Armandroff 1990). I_0^{TRGB} is the magnitude of the TRGB, and can be estimated from the I_0 luminosity function as shown in Fig. 8 for both inner and outer field. Several authors have proposed quantitative methods for determining the TRGB position by convolving the luminosity function with a properly defined edge-detection filter (Lee *et al.* 1993; Sakai *et al.* 1996). An application of such filters to our data does not, however, result in a clean and unique edge detection. This is especially true for the outer field data which shows high frequency variations. We therefore adopt the conventional method based on eye estimates. From the overall shape of the luminosity distribution, we see a sudden change at the same location ($I_0^{\text{TRGB}} = 20.30 \pm 0.04$) for both fields, where we have assigned an uncertainty for these estimates as the bin half-width. Our value of I_0^{TRGB} is 0.15 and 0.25 mag fainter than two previous estimates from lower-resolution ground-based data by Davidge (1994) and Mould *et al.* (1983), respectively. The color at the TRGB was estimated using the median value of $(V-I)_0$ for stars in the range $20.3 < I_0 < 20.4$ and $1 < (V-I)_0 < 2.5$. This yields a value of $(V-I)_0^{\text{TRGB}} = 1.77 \pm 0.02$ for the outer field, and $(V-I)_0^{\text{TRGB}} = 1.91 \pm 0.03$ for the inner field, respectively. The distance and metallicity based on the measurements of the TRGB of both inner and outer fields, are similarly derived by iteration using the relations given above. The results are: $(m-M)_0 = 24.37 \pm 0.06$, $[\text{Fe}/\text{H}] = -1.00 \pm 0.03$ based on the outer field TRGB, and $(m-M)_0 = 24.36 \pm 0.06$, $[\text{Fe}/\text{H}] = -0.91 \pm 0.03$ based on the inner field TRGB. The distances based on the TRGBs of the

FIG. 9. The variation of mean metallicity (top panel) and metallicity dispersion (bottom panel) with radius. The inner field data are presented in solid dots, and outer field data in open circles.

two fields agree very well, although the mean metallicity in the two fields appears to differ at a moderately significant level. Again, the quoted errors here do not include any uncertainty in the adopted calibration relations.

4.3 Metallicity Dispersion

Figures 4 and 5 show a measurable color-width in the observed RGBs, indicating the existence of metallicity dispersion in the galaxy. We estimate the color-width of the RGB by calculating the sigma of the $(V-I)_0$ color in the luminosity range $-3.1 < M_I < -2.9$ with a 3σ iterative rejection. This yields a width of the RGB at $M_I \sim -3$ of $\sigma_{V-I} = 0.16$ and $\sigma_{V-I} = 0.13$ mag in the inner and outer field respectively. These are significantly larger than the mean photometric uncertainties in colors at this level, which are 0.04 and 0.03 mag per star for the two fields, respectively. These uncertainties reflect the photo statistics and data reduction errors from the DAOPHOT/ALLFRAME program (see Stetson 1994). Using the color-metallicity relation adopted above, we estimate the mean metallicity dispersion of $\sigma_{[Fe/H]} = 0.52$ in the inner field, and $\sigma_{[Fe/H]} = 0.42$ in the outer field. Metallicity dispersion in NGC 147 has been previously reported by Mould *et al.* (1983), Saha *et al.* (1990), and Davidge (1994).

The metallicity-color relation of Da Costa & Armandroff (1990) was based on very old stellar populations in Galactic globular clusters. However, the few EAGB stars observed in NGC 147 indicates the presence of a (small) younger stellar population in the galaxy, which will act as an additional source of color broadening for the RGB. Our estimates for the metallicity dispersion above should therefore be regarded as upper limits.

4.4 Mean Distance and Comparison with Other Determinations

The distance and metallicity determination based on HB and TRGB are summarized in Table 3. The distance based on the HB appears to be marginally larger than that based on the TRGB, but the agreement is quite reasonable considering

the uncertainty introduced by the various calibration relations which could be at a level of 0.1 mag or larger. We simply adopt a straight average of the three distance values as our best estimate for the distance of NGC 147: $(m-M)_0 = 24.39 \pm 0.05$. We note that the mean luminosity-metallicity relationships for HB stars derived by different investigators vary considerably. For example, Carney *et al.* (1992) presented a mean luminosity-metallicity relation for the RR Lyrae stars, $M_V = 0.15(\pm 0.01)[Fe/H] + 1.01(\pm 0.08)$. If this relation is used to define the distance scale, then our derived distance modulus from the two methods are both expected to be brighter by about 0.2 mag.

Two recent estimates of the distance to NGC 147 are given by Mould *et al.* (1983) and Saha *et al.* (1990). Mould *et al.* derived a distance modulus of 24.0 ± 0.15 , based on the TRGB method, using a slightly different calibration. This discrepancy is largely due to the difference in the estimated TRGB magnitudes as pointed out above. Saha *et al.* (1990) reported a distance modulus of 23.92 ± 0.25 based on their study of RR Lyrae variable stars. Their distance scale is based on a luminosity-metallicity relation $M_V = 0.19[Fe/H] + 1.03$ and an adopted metallicity of $[Fe/H] = -1.2$. Using the distance scale adopted in this paper (and also our derived metallicity), their distance modulus would be converted to 24.07 mag. This is still more than 0.3 mag brighter than our estimate. This discrepancy is completely attributed to the difference between the derived mean magnitude of our HB stars and that of their RR Lyrae stars. As discussed above, we derived a mean HB magnitude of $V_0 = 25.09 \pm 0.02$ using some 600 HB stars, while Saha *et al.* derived a mean g magnitude of the RR Lyrae stars of $M_g = 25.25 \pm 0.10$, which corresponds to $\langle V_0 \rangle = 24.71$, assuming a mean color of $\langle g_0 \rangle - \langle V_0 \rangle = -0.04$ for RR Lyraes, and an extinction of 0.576 mag at V adopted in this paper. So the difference is at the 3 sigma level in the sense that the RR Lyrae magnitude is brighter. This may reflect a Malmquist-like bias in the measurement of RR Lyrae stars near the detection limits with ground based instruments, or it may be due to errors in the magnitude scale. Since the fields observed with *HST* do not overlap with the earlier RR Lyrae observations, we can not make a star-by-star comparison.

5. VARIATION OF STELLAR POPULATION WITH GALACTOCENTRIC RADIUS

Significant differences are clearly visible between the CMDs of our two fields. A difference in metallicity and metallicity dispersion were also illustrated quantitatively in the previous section. Our deep photometric data in the two fields, with a large number of detected stars and a wide radial coverage in the galaxy, enables us to examine in more detail the radial distribution of the various components of the stellar populations in NGC 147.

5.1 Radial Distribution of Metallicity & Metallicity Dispersion

Figure 9 shows the variation of the mean metallicity and metallicity dispersion with distance to the center of the galaxy. Both quantities were calculated using the color-

FIG. 10. The radial distribution of EAGB stars. Top panel: the number density of the EAGB stars in arcsec^{-2} . Middle panel: the number density ratio of EAGB stars to the red-clump stars. Bottom panel: the number density ratio of EAGB stars to all stars. The inner field data are presented in solid dots, and outer field data in open circles.

metallicity relation as given in Sec. 4. The filled points in Fig. 9 are based on data in the inner field, and the open-circle points are based on the outer field data. The error bars reflect the statistical plus photometry uncertainty in our data, but do not include any uncertainty in the adopted relation, for which we note that Da Costa & Armandroff (1990) have quoted a dispersion of 0.07 in their fit. The figure shows a clear trend of decreasing metallicity dispersion with radius. The mean metallicity, on the other hand, does not seem to show a significant monotonic variation with radius, though there appears to be a very weak overall tendency of *increasing* metallicity with radius. This tendency is in contrast to the decreasing metallicity seen in most other elliptical galaxies (e.g., Davies *et al.* 1993). If the star formation activity in a typical galaxy starts from the center and propagates outward on average, a positive, or even a zero metallicity gradient must be the result of a very powerful gas-mixing mechanism which re-distributes the heavy elements effectively during subsequent star formation events.

The apparent metallicity dispersion and its variation with galactocentric radius may partly reflect a radial variation of age mixture. As we will see below, the EAGB stars are more concentrated in the center of the galaxy, implying more age mixture in the center than at the outer part of the galaxy. However we are not able to quantify how much of the observed radial variation is contributed by an age-mixing effect. The average difference in photometric errors in the two fields is only 0.01 mag at the level of $M_I = -3$, and so would not produce an apparent metallicity dispersion gradient.

5.2 Radial Distribution of the Asymptotic Giant Branch Stars

The presence of EAGB stars in both inner and outer fields (see the CMDs in Figs. 4 and 5) indicates that an intermediate-aged stellar population exists in NGC 147. It is visually evident from the CMDs that the fraction of EAGB stars is much higher in the inner field than in the outer field.

We now quantify this tendency by calculating the number density of the EAGB stars as a function of galactocentric radius.

We identify EAGB stars above the RGB tip as those in the magnitude and color range of $19 < I_0 < 20.3$ and $1.4 < (V - I)_0 < 3.9$. Figure 10 shows the radial distributions of EAGB stars. The top panel shows the distribution of the number density of EAGB stars (in arcsec^{-2}); the middle panel shows the distribution of the number density ratio of EAGB to the red clump stars ($24.5 < V_0 < 25.5$ and $0.5 < (V - I)_0 < 1.5$); and the bottom panel is the distribution of the number density ratio of EAGB to all detected stars. The inner and outer field data are plotted as solid and open points, respectively. The error bars were calculated assuming Poisson noise on the detected numbers of stars. It is apparent that the EAGB number density decreases with increasing galactocentric radius. The density is about 0.03 arcsec^{-2} near the center and gradually drops to about $0.003 \text{ arcsec}^{-2}$ at $R \sim 3'$, and appears to stay at this level beyond this radius. More interestingly, the relative number of EAGB stars with respect to both the RC stars and all stars also show a systematic decrease with galactocentric radius. This implies that the EAGB stars, or an intermediate-aged population of stars, are more centrally concentrated than the majority of the older stars. We note that the decrease of the relative number of EAGB stars with increasing radius explains the apparently conflicting results about the existence of EAGB stars in NGC 147 in two previous studies based on ground-based data: Mould, Kristian & Da Costa (1983) detected no EAGB stars in a field some 5 arcmin away from the center, whereas Davidge (1994) detected a small population of EAGB stars in a central region.

It is important to note that the observed ratios of $N_{\text{EAGB}}/N_{\text{RC}}$ and $N_{\text{EAGB}}/N_{\text{ALL}}$ are higher than their true values because of completeness effects. Our estimate of the completeness function based on artificial star simulation shows that the completeness at the level of the RC is about 50% for the inner field and 65% for the outer field. This implies a completeness correction of about a factor of 2 for the observed ratios. The relative difference in the completeness of the two fields also tends to decrease the observed radial variation, but the effect is only a few percent of the observed total amplitude. So the observed radial variation of $N_{\text{EAGB}}/N_{\text{RC}}$ and $N_{\text{EAGB}}/N_{\text{ALL}}$ cannot be a result of completeness effect. Our experiments also show that the radial variations of these ratios are not sensitive to our adopted TRGB magnitude ($I_0^{\text{TRGB}} = 20.30$).

As shown in Figs. 4 and 5, the EAGB in NGC 147 barely extends above the tip of the RGB, so the definition of “EAGB stars” is not simple, e.g., TRGB miras at peak light could be confused as EAGB stars. We assume this effect is minor. Using bolometric corrections of Bessell & Wood (1994), we find that most NGC 147 EAGB stars have $-3.5 > M_{\text{bol}} > -4$. A few more luminous EAGB stars with $M_{\text{bol}} \sim -5$ are present in both fields, but they are a small minority of the total EAGB population, in agreement with Davidge’s (1994) results. Empirical calibrations of EAGB star evolution derived from studies of Magellanic Cloud star clusters by Frogel *et al.* (1990) suggest that low metallicity,

FIG. 11. The radial distribution of HB stars in the outer field. Top panel: the number density of the HB stars in arcsec^{-2} . Second panel from top: the number density ratio of HB stars to RGB stars. Third panel from top: the number density ratio of HB stars to RC stars. Bottom panel: the number density ratio of HB stars to AGB stars.

low luminosity AGB stars have progenitor masses of $<2 M_{\odot}$. This agrees with the absence of a main sequence in our field for luminosities of $M_V < 1$, implying that significant star formation activity in NGC 147 ceased more than 1 Gyr ago.

Theoretical models of AGB star populations are sensitive to several parameters, including mass-loss rates and abundances (e.g., Groenewegen & Jong 1993). Low luminosity AGB stars are expected to have low core masses, and therefore could be produced from a range of initial stellar masses. For example, the models of Lattanzio (1986, 1991) suggest possible ages ranging from a few to <10 Gyr, with the precise age distribution depending on mass loss rates and other factors. However, despite the uncertainties, it is clear that substantial star formation occurred in NGC 147 well after the dominant, old metal-poor stellar population was produced.

We are in agreement with the previous analysis by Davidge (1994) in finding that NGC 147 resembles the other two M31 dE companions, NGC 185 and NGC 205, in having a centrally-concentrated, intermediate age stellar population (Davidge 1992; Lee *et al.* 1993). NGC 147, however, differs from the other two systems in having neither young stars nor evidence for massive molecular clouds which could form stars. As a result it is not surprising that the AGB stars in NGC 147 should be oldest and thus appear to have the lowest mean luminosity of the three M31 dwarf elliptical companions.

5.3 Radial Distribution of the Horizontal Branch Stars

While a horizontal branch is clearly detected in the outer field of the galaxy (see Fig. 5), its presence is not obvious in the inner field (Fig. 4). The stars just below the level of HB

are considerably spread in color due to the larger photometric errors (the inner field is not as deeply exposed as the outer field) as well as a broader RGB for the inner field stars. We show in Fig. 11 the radial distributions of (1) the number density of HB stars in units of arcsec^{-2} , (2) the density ratio of the HB to RGB stars, (3) the density ratio of HB to EAGB stars, and (4) the density ratio of HB to red clump stars. These calculations are based on the outer field only, and again the EAGB stars are defined as those above the RGB tip ($19 < I_0 < 20.3$ and $1.4 < (V-I)_0 < 3.9$), the RC stars are those with $24.5 < V_0 < 25.5$ and $0.5 < (V-I)_0 < 1.5$, and the RGB stars are selected in the range $V_0 < 24.5$, $I_0 > 20.3$, and $0.5 < (V-I)_0 < 2.5$. We see that the number density of the HB stars in the outer field does not show a strong decreasing trend with radius, and the density of the HB stars relative to other characteristics stars tends to increase with radius.

The observed radial profiles of the three density ratios in Fig. 11 are all in the same sense that could be produced by a differential completeness effect (a radial dependence of completeness due to crowding). However, this effect is unlikely to be significant in our case. First, our simulations using artificial stars do not show any noticeable change in completeness from chip to chip in the outer field; and secondly, if completeness is the cause, we would expect the $N_{\text{HB}}/N_{\text{EAGB}}$ ratio to show the largest percentage variation, the $N_{\text{HB}}/N_{\text{RGB}}$ ratio the second largest, and the $N_{\text{HB}}/N_{\text{RC}}$ ratio the smallest or nearly zero variation; the observed relative variations in these ratios as seen in Fig. 11 do not follow this expectation. We conclude that the observed radial variations of the HB stars relative to other stars are real.

This gradient in the distribution of the HB stars implies an age variation with radius in the sense that stars at larger radii are generally older. The age gradient model is also consistent with the distribution of EAGB stars as described in the previous section. Finally, one should note that, although completeness is not responsible for the observed radial profiles of the density ratios, the overall scale of the observed ratios of $N_{\text{HB}}/N_{\text{RGB}}$ and $N_{\text{HB}}/N_{\text{EAGB}}$, but not $N_{\text{HB}}/N_{\text{RC}}$, are subject to a correction for completeness by a (multiplicative) factor of up to 1.5, given a completeness of about 65% at the HB level.

The properties of the HB depend on factors other than age, and these could also be important in NGC 147. For example, the ratio of HB to RGB stars, and also the ratio of HB to RGB+EAGB stars are good indicators of the helium abundance for a single population stellar system like the Galactic globular clusters (Iben 1968; Buzzoni *et al.* 1983). Obviously these methods cannot be directly applied to a galaxy like NGC 147, which has a complicated mixture of ages and abundances.

It is illustrative to compare the distribution of HB+RC stars in NGC 147 with those in other elliptical companions of M31. Da Costa *et al.* (1996) have recently studied the stellar population in the dwarf spheroidal galaxy Andromeda I based on *HST*/WFPC2 observations. Their study reveals that the HB stars in Andromeda I are predominantly red, but a small number of blue HB stars are also present, mostly at

larger radii. They interpret this radial variation of HB stars as an indication of a minority population of older stars at large radii in Andromeda I; this age gradient is broadly consistent with our conclusion for NGC 147. However, some detailed differences may exist. For example, our data cannot distinguish a blue from a moderately red HB in NGC 147, while a blue HB is present in Andromeda I.

Another extreme example of HB+RC morphology is that of M32. Observations with WFPC2 by Grillmair *et al.* (1996) shows a pronounced red clump, a moderately broad RGB with strong redwards extension, and no evidence for a substantial HB. As in our central observations, the M32 data are too shallow to completely exclude a HB. However, it appears that NGC 147 is intermediate between Andromeda I and M32 in terms of HB and red clump morphology, and also in terms of the mean metallicity deduced from the RGB.

The fundamental variables underlying the distribution of stars in the CMD plane include ages, chemical abundances, and the differences (if any) in the initial mass functions of each star formation event in the galaxy. Recovering these parameters from the photometric data is one of the central goals of stellar population studies of galaxies. Unfortunately, the problem is difficult because within some regions of a CMD, variables such as age and metallicity can play off against one another. The lack of an adequate quantitative method for solving this problem has significantly hampered our ability to understand star formation histories in galaxies. To improve this process we have developed a very sensitive and quantitative global CMD fitting technique, and in a future paper we will apply this approach to an analysis of the star formation history of NGC 147 (Han *et al.* 1997).

6. SUMMARY

We have obtained deep F555W (*V*) and F814W (*I*) images in two fields of the Local Group dwarf elliptical galaxy NGC 147 with the *HST*/WFPC2. One major conclusions are summarized below.

- The high resolution images show no indication of the presence of dark clouds, and no main sequence stars are detected with $M_V \leq 1$. Evidently this galaxy no longer contains a significant Pop I stellar component.
- No new star clusters are found in our two fields; the only star clusters are the previously known globular clusters.
- The color-magnitude diagram (CMD) is dominated by a well-defined red giant branch (RGB), with a prominent red clump (RC) plus a small fraction of extended asymptotic giant branch (EAGB) and horizontal branch (HB) stars. The CMD varies significantly with galactocentric distance. The presence of the EAGB stars agrees with an earlier study by Davidge (1994), but we are for the first time able to accurately map the HB and RGB.
- Using both HB stars and the brightness of the tip of the RGB, we derive a mean distance to NGC 147 of $(m - M)_0 = 24.39 \pm 0.05$, where the quoted error reflects only the uncertainty in our photometry.

- The mean metallicity $[\text{Fe}/\text{H}]$ estimated using the RGB color, is -0.9 in the inner field, and -1.0 in the outer field; a weak tendency of increasing metallicity with radius may exist in the outer field. Metallicity dispersion is present in the galaxy, and appears to increase toward the center of the galaxy, but this variation also could be produced by an age mixing effect.
- The detection of some EAGB stars implies the presence of a small intermediate age stellar population in NGC 147. The number density of EAGB stars relative to other stars decreases with galactocentric radius, indicating that the younger stars are more centrally concentrated than the older stars. Thus NGC 147 follows the pattern seen in the other two M31 dwarf elliptical companions, NGC 185 and NGC 205, where younger stars are centrally concentrated.
- About 600 HB stars are detected in the outer field. The number of HB stars relative to the RC and RGB stars increases with radius, implying a mean age gradient in the galaxy (or at least the outer part), in the sense that more older stars are found at larger radii. This appears to be consistent with the model derived from the EAGB stars.

Our initial analysis indicates that the stellar body of NGC 147 formed over a considerable time span. From the presence of a HB in the outer regions of the galaxy, a classical Pop II stellar component is present with a probable age of 10 Gyr or more. On the other hand the strong concentration of stars in the RC and the existence of EAGB stars are indicators of a large and perhaps even dominant intermediate age stellar population. Star formation in NGC 147 was an extended process that covered several Gyr between its inception and effective end.

The qualitative history of star formation in NGC 147 does not readily fit the standard evolutionary models for dwarf elliptical galaxies. At one extreme models with a strong initial collapse, such as those computed by Hensler *et al.* (1993), experience most of their star formation during a few free-fall times after the initial collapse. These models would make a galaxy with too much pure Population II. Another limit is from delayed collapse models (e.g., Rees & Ostriker 1977; Babul & Ferguson 1996) where most stars are formed in a starburst event more recently than $z = 1$. For reasonable cosmological models this makes all of the stars of intermediate age, which disagrees with our observations. Evidently a less extreme model with a wider mix of stellar ages is required, and we will return to these issues as part of our future quantitative modeling of the NGC 147 star formation history (Han *et al.* 1997).

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FIG. 2. Mosaic of the F555W images of the inner field of NGC 147.

Han *et al.* (see page 1002)

FIG. 3. Mosaic of the F555W images of the outer field of NGC 147.

Han *et al.* (see page 1002)