THE STELLAR CONTENT AND STAR FORMATION HISTORY OF THE LATE-TYPE SPIRAL GALAXY NGC 300 FROM HUBBLE SPACE TELESCOPE OBSERVATIONS

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ABSTRACT

We present the first Hubble Space Telescope (HST) WFPC2 V and I photometry for the Sculptor Group galaxy NGC 300 in four fields ranging from the center to the outer edge. We have made the first measurement of the star formation histories in two disk fields: the oldest stars were born at similar epochs and formation activity increased but at different mean rates. The main disk stellar population is predominantly old, consisting of red giant branch (RGB) and asymptotic giant branch (AGB) stars, based on a synthetic color-magnitude diagram analysis. The metallicity $Z$ is found to have been less than 0.006 (or 0.33 $Z_{\odot}$), with no evidence for significant change in mean $Z$ over time in both disk fields. In the central region, we find a dearth of bright stars with respect to the two disk fields that cannot be explained by observational effects. Taken at face value, this finding would agree with the Davidge report of suppressed star formation there during the past $10^9$ yr with respect to his disk fields at larger radii; but the possibility remains that significant central extinction affects our finding. We have also determined the first distance modulus estimate based on the tip of the red giant branch method. On the Cepheid distance scale of Ferrarese et al., we find $(m-M)_0 = 26.56 \pm 0.07 \pm 0.13$ mag and a similar value from the Cepheid-independent empirical method of Lee, Freedman, & Madore, both in good agreement with the Cepheid distance determined by Freedman et al. A discrepancy between this value and the theoretical calibration of the red giant branch tip magnitude method remains. Finally, we report a newly detected young (up to about 10 Myr) stellar association of about average size (~140 pc) in one of the disk fields.

Key words: galaxies: distances and redshifts — galaxies: formation — galaxies: general — galaxies: spiral — stars: formation

On-line material: color figures

1. INTRODUCTION

In recent years real observational evidence has emerged indicating that spiral galaxies assembled their components (disk, halo, bulge) at different times and on different timescales (for example, Andredakis, Peletier, & Balcells 1995; Ibata et al. 2001, and references therein; and Gratton et al. 2003, based on ages of a small sample of three Milky Way globular clusters). Galaxy formation studies are usually performed using surveys; however, it is obviously important to take representative examples of Hubble types and study them in detail. In order to learn about galaxy formation and evolution in detail, there are three basic diagnostic tools, namely morphology, kinematics, and stellar populations. Of these, perhaps the most direct way of studying the evolution of a galaxy’s stellar component is with diffraction-limited imaging with the Hubble Space Telescope (HST).

NGC 300 is typical of a late-type spiral of type SA(s)cd (Tully 1988) and the brightest of five main spiral galaxies that comprise the Sculptor group. With a Cepheid-based distance estimate of $(m-M)_0 = 26.53 \pm 0.07$ mag (Freedman et al. 2001) and its near face-on orientation, NGC 300 is well suited to studies of its stellar content. In the past decade, many studies have been devoted to the bright young stellar population in this galaxy. Consequently, there are now several signs pointing to recent massive star formation, namely the presence of Wolf-Rayet stars (e.g., Schild et al. 2003) and individual supergiants (Urbanek et al. 2003; Bresolin et al. 2002a, 2002b; Schild & Testor 1992; Humphreys & Graham 1986), young stellar associations (Pietrzyński et al. 2001), Cepheids (Pietrzyński et al. 2002), H ii regions (e.g., Soffner et al. 1996; Deharveng et al. 1988), supernova remnants (Pannuti et al. 2000), and X-ray emission (Read & Pietsch 2001). The older stellar populations have also been targeted (see Davidge 1998 and references therein), but high angular resolution imaging ($\lesssim 0.05$) is needed to probe this fainter stellar population, especially in the central regions.

In this paper, we present the first study of the resolved old, intermediate-age, and young stellar populations of the spiral galaxy NGC 300 based on color-magnitude diagrams (CMDs) from HST observations. The main motivation for optical imaging data is sensitivity to a relatively wide range of temperatures in non- or marginally extincted fields. This paper is organized as followed. Data and data reduction are described in § 2. An overview of the stellar populations based on CMDs is given in § 3. The distance measurement based on the tip magnitude of the red giant branch is described in § 4, and the issue of internal extinction is discussed in § 5. The population of young stars is discussed in § 6, and the derivation of the chemical enrichment and star formation history is presented in § 7. Finally, we discuss our findings in § 8 and summarize them in § 9.
examined archive I(814)- and V(547/555/606)-band frames from four HST WFPC2 pointings. These are listed in Table 1, and their WFPC2 footprints are superimposed on an image from the ESO Wide-Field Imager (ESO WFI) in Figure 1. Data reduction details are given by Bagget et al. (2002) and Holtzman et al. (1995).

The photometry of the stars in NGC 300 was derived using the HSTphot (Dolphin 2000a) point spread function (PSF)–fitting photometry package, which is designed for optimal reduction and analysis of WFPC2 data and has been used recently in a number of stellar population studies (e.g., Méndez et al. 2002, and references therein). The code utilizes a library of PSFs to account for PSF position dependence and is optimized for the undersampled PSFs present in WFPC2 data. This package was also used to mask bad pixels and columns using the data-quality image and to reject cosmic rays in the images. For transformation of the WFPC2 photometry into the standard V- and I-band system, stellar magnitudes are calibrated by HSTphot using the charge transfer efficiency and zero-point magnitude corrections derived by Dolphin (2000b). The photometry is reported to be accurate to 0.02 mag (Dolphin).

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| Field | Radial Distancea (arcmin) | Radial Distanceb (kpc) | Date | Filter | Number of Frames | Integration Time (s) |
|-------|--------------------------|------------------------|------|--------|------------------|---------------------|
| F2    | 0.44                     | 0.4                    | 2001 May 06 | F814W/F547M | 2/4             | 300/400             |
| F1    | 5.99                     | 5.1                    | 2001 Jul 02 | F814W/F606W | 2/2             | 300/300             |
| F3    | 7.12                     | 6.0                    | 2001 Sep 13 | F814W/F555W | 2/2             | 500/500             |
| F4    | 12.84                    | 10.9                   | 2001 Jun 20 | F814W/F606W | 4/4             | 500/500             |

**Notes:**

- a Separations from galaxy center to the coordinates listed in the data pointings table (nominally the middle of the field of view) are taken from MAST, the multimission archive at STScI.
- b Deprojected radial distance in kpc based on an inclination of 46° (Tully 1988).

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The field size is 34′6 square. WFPC2 positions: r = 5′99 (F1), 0′44 (F2), 7′12 (F3), and 12′84 (F4). North is up and east is left. [See the electronic edition of the Journal for a color version of this figure.]
with coordinate transformation rms residuals of the order of 0\textquotesingle 02 in both axes.

Artificial star tests have been performed using HSTphot for the $V$-band magnitude range 20–28 (mag) and $V-I = -0.5 - 3$ (mag), which are approximately the ranges of interest in our CMDs. Each test consisted of choosing a star from the $V$-band magnitude and color range, adding it to both the $V$ and $I$-band images, and then the image was reanalyzed by HSTphot. In this way, the effect of creating additional crowding of stars has been minimized. This was repeated several thousand times for each WFPC2 frame. From all of the tests, a database of measurements for different positions and input $V$-band magnitudes and colors is built. The ratio of the number of recovered stars to the number of added stars in a magnitude range indicates the statistical probability of recovering a star in that magnitude range. The database also allows the photometry errors (recovered minus input magnitudes) to be determined for each bandpass.

Figure 2 plots the completeness factor versus magnitude for our four fields, which are situated at different radial distances from the center of NGC 300. A completeness plateau occurs for the brightest stars, because their signal-to-noise is sufficiently high and crowding affects these stars equally. A completeness of 100% is not reached because of bad pixels.\(^3\) For each bandpass, the completeness is different at each pointing. The F4 field has the longest integration time, providing the faintest magnitude limit, and the crowding factor is shifted accordingly to fainter magnitudes relative to the other integrations. There is a strong difference between the functions of the innermost and outermost fields. Indeed, detectability in the inner field is less efficient than in the outer fields largely because of severe crowding, as well as shorter integration times. The $V$-band functions have fainter limiting magnitudes than those in the $I$-band largely because of lower HST WFPC2 throughput in the $I$-band.

For the final photometry list used in this study, we select those objects flagged as valid stars in both bandpasses and that have $S/N > 5$, $\chi^2 < 5$, $-0.5 < \text{sharpness} < 0.5$, and $\sigma_{V,I} < 0.25$ mag. After selection, there are 7614, 1421, 3467, and 235 stars in the F1, F2, F3, and F4 fields, respectively. In the present paper we apply the selection criteria to stars at $I < 23$ mag whenever star counts in color-magnitude diagrams are analyzed. At this magnitude limit and brighter, the artificial star tests find the data to be at least 90% complete, and stars

\(^3\) The number of pixels deemed to be bad in the unvignetted portion of each chip/frame is on the order of 1% (which includes cosmic ray events, bad columns, and pixels flagged as bad in the STScI data quality file).
intrinsically brighter than $I = 23$ mag will only be missed if they are physically obscured, e.g., by dust.

3. THE STELLAR CONTENT OF NGC 300 FROM THE COLOR-MAGNITUDE DIAGRAM

Figure 3 shows the CMDs for the four WFPC2 fields described in Table 1. These fields occur at radial distances ranging from 0.44 to 12.8 or deprojected radial distances of 0.4 to 10.9 kpc at NGC 300 for a distance of $2.02 \pm 0.07$ Mpc (Freedman et al. 2001).

The F1 and F3 fields overlap with parts of different spiral arms in NGC 300 (see Fig. 1), and the CMD of each region provides a sketch of some of the stellar content there. The most prominent feature is the red giant branch (RGB) structure, which is very similar to those observed in nearby dwarf irregular galaxies (NGC 6822: Gallart, Aparicio, & Vilchez 1996; Sextans A: Dohm-Palmer et al. 2002). This structure is typical of a galaxy that is clearly composed of an ancient stellar population: it is the locus of old and intermediate-age RGB stars, low asymptotic giant branch (AGB) stars, and blue-loop stars some hundred million years old. A significant number of red bright stars are observed above the tips of the fiducial RGB ridgelines, and they could be intermediate-age AGB stars covering a wide range of ages and metallicities. In addition, there is also an important population of young stars (age $< 1$ Gyr); these include main sequence stars, core helium burning stars in the blue supergiant and/or in the blue loop region at $V-I \leq 0.9$ (mag), and red supergiants at $0.9 \leq V-I \leq 1.3$.

The CMDs in these different regions also display some marked differences in morphology that cannot be fully explained by differences in observational effects. Most notably, the CMD of the innermost region appears stretched to red colors, mainly because of severe stellar crowding as judged by the completeness tests of §2. Incidentally, this crowding issue highlights the need for near–diffraction limited imaging at extremely large (>20 m class) optical/IR telescopes. We see an absence of stars at $I < 22$ mag in field F2 that is not explained by incompleteness; the significance of this is discussed later in §§5 and 6. Finally, we see a dense string of stars at $V-I \sim 0$ and $I < 23$ mag in the F1 field that could well be the stellar main sequence; the finding is especially noteworthy because incompleteness would tend to suppress such features (Fig. 4).

For a comparative analysis of the star counts in the fields at intermediate radii (F1 and F3), we determined the ratio of star counts in three age-sensitive CMD boxes to the star counts in

![Fig. 3.—Four $I$ and $V-I$ CMDs for WFPC2 pointings in NGC 300. The plotted data consist of all stars with valid photometry (see §2). From metal-rich (right) to metal poor (left), dereddened globular cluster red giant branch ridgelines (solid lines) are for 47 Tuc, $[\text{Fe/H}] = -0.71$, NGC 1851, $[\text{Fe/H}] = -1.29$, and NGC 6397, $[\text{Fe/H}] = -1.91$. Included are photometry bars associated with $V-I = 1$ mag.](image-url)
The data indicate that the F1 field has, on average, 3–4 times more stars, or similarly, that it is brighter by 1–1.5 mag than the F3 field. We also find that there is a young population gradient in the F1 field, probably because it covers a possible spiral arm star-forming region (Fig. 5). Finally, unlike the old populations (>1 Gyr), there is a marked difference in the relative number of young stars in the two fields. In the outermost field (F4), there is a stark absence of bright stars ($I < 24$ mag) with respect to the F1 field. As the surface brightness difference with respect to the F1 field is significant (~2.7 mag) as measured by Carignan (1985), our observation of a dim disk field would be expected.

The expected number of foreground stars contaminating our CMD was estimated from the Kim, Sung, & Lee (2002) study, galactic models, and the Hubble Deep Field to be about 1 and about 5 per pointing at $I < 17$ and $I < 23$ mag, respectively. The number of contaminating galaxies was estimated for several fields of the Medium Deep Survey (Griffiths et al. 1994), and our selection criteria (stars brighter than $I = 23$ mag) is expected to be robust against background galaxy contamination at these bright magnitudes, which is estimated to be $1 \pm 1$ per WFPC2 pointing and thus an unlikely source of contamination, which was not assessed by the artificial star test. The expected

![Diagram](image_url)
number of (unobscured) globular clusters in the WFPC2 fields based on Kim et al. (2002; hereafter referred to as K02) is at most 1 ± 1. Such objects would have $V-I$ colors mostly in the range 0.9–2.0 and integrated $I$-band magnitudes of about 16–17 mag at the distance of NGC 300 based on the Milky Way globular cluster system (Harris 1996).4

4. TRGB DISTANCE TO NGC 300

The most recent estimate of the distance to NGC 300 has been made by Freedman et al. (2001) using Cepheids. In the context of distance verification, it is important to verify this estimate using a different distance indicator. We have used the dereddened magnitude of the tip of the red giant branch (TRGB), $I_{0,\text{TRGB}}$, to derive the distance modulus of NGC 300 based on the widely used approach described by Lee, Freedman, & Madore (1993, hereafter LFM93), which typically has errors less than 10%. It has been assessed theoretically by Salaris & Cassisi (1998; hereafter SC98) who found that differences between TRGB and Cepheid distances are not correlated with metal content. Incidentally, it is the first such distance measurement for NGC 300, although distances to several other Sculptor Group galaxies have been measured previously using the same method (Karachentsev et al. 2003).

For the $I_{\text{TRGB}}$ determination, we consider the F1 and F3 fields and ignore the remaining two fields because of a low number of stars and blending in the innermost field. To reduce the contribution of young/intermediate age stars, we selected stars with $(V-I) > 1.5$ mag. To measure the $I$-band magnitude of the TRGB, we applied the edge-detection method described by Sakai, Madore, & Freedman (1996). First, for a sequence of magnitude values, we created a smoothed luminosity function $\Phi(m)$ by replacing each magnitude value by a Gaussian distribution whose width (standard deviation) is the magnitude uncertainty (e.g., Fig. 6, third panel from top). The edge-detection response is

$$\text{ED} = \Phi(m - \bar{m}) - \Phi(m + \bar{m}),$$

where $\bar{m}$ is the average $\sigma_m$ at $m = 0.05$ mag. ED was calculated at $I$-band magnitude steps of 0.01 mag. Next, we selected 85% of these stars at random, and as a first estimate of the $I_{\text{TRGB}}$ magnitude, we recorded the magnitude at which the filter response is a maximum at $I < 22.7$ mag. To determine the uncertainty in the tip magnitude, we performed a so-called bootstrap resampling of the data by repeating the procedure 500 times. We then fitted a Gaussian to a histogram of the tip magnitude estimates (binned at 0.01 mag). The peak magnitude from the Gaussian fit is taken as $I_{\text{TRGB}}$, and the error in the Gaussian is taken as the uncertainty (Fig. 6, top). These values are given in Table 3. For the F3 field, the tip magnitude estimate is not reliable because of the low number of star counts, as is seen by the poor convergence of tip estimates (Fig. 7, top).

To determine how these values depend on the fraction of stars selected, we varied the fraction selected from 0.6 to 0.9 and got the same $I_{\text{TRGB}}$ value with only a slightly larger uncertainty. To test for a possible bias on the TRGB magnitude caused by incompleteness, we multiplied the smoothed luminosity function by a monotonically decreasing function $[1.0:0.80]$ in the magnitude range 22–24 mag and found no sensitivity to this. Another source of potential bias comes from smoothing the luminosity function. Cioni et al. (2000) reported

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4 We have checked whether some of the candidate globular clusters from Kim et al. (2002) appear in the WFPC2 frames. One of them (their ID 8) occurs in the F1 field (chip 1), while the other (ID 6) appears in the center field (chip 1). However, both objects are saturated in the WFPC2 frames, and there are neighboring stars; further study of them has not been pursued.
the Sobel filter to be a biased estimator of the TRGB and that the bias depends on the amount of smoothing in the luminosity function at the location of the TRGB. To test our sensitivity to smoothing, we varied the smoothing window in the range 0.04–0.06 mag and find negligible change in the mean tip magnitude and only a slight change in errors.

The absolute $I$-band extinction, $A_I$, toward NGC 300 can be derived, assuming the reddening law $R_V = \frac{A_V}{E(B-V)} = 3.1$ and $A_I/A_V = 0.48$ (Cardelli, Clayton, & Mathis 1989). From the COBE DIRBE and IRAS dust maps analyzed by Schlegel, Finkbeiner, & Davis (1998; hereafter SFD98), we have $E(B-V) = 0.013$ mag at its Galactic coordinates ($l = 299.21$, $b = -79.42$ from SIMBAD), which is similar to the 0.008 mag from the lower resolution dust maps of Burstein & Heiles (1982; hereafter referred to as BH82). Adopting the SFD98 value, we get $A_V = 0.039$ mag, and $A_I = 0.019$ mag. The values are included in the dereddened $I$-band magnitude of the TRGB in Table 3. The possible presence of significant amounts of dust in the observed fields is explored in more detail in § 5.

Next, we calculate $M_{I,TRGB}$, using three methods for comparison. In the first method, we adopt the value $M_{I,TRGB} = -4.06 \pm 0.07$ (random) $\pm 0.13$ (systematic) mag from Ferrarese et al. (2000; hereafter referred to as F00). They treated the TRGB as a secondary distance indicator and calibrated a zero point from galaxies with Cepheid distances. The calculated distance modulus, $(m-M)_0$ is therefore $26.56 \pm 0.07$ (random) $\pm 0.13$ (systematic) mag, which is in good agreement with the recent Cepheid-based estimate of Freedman et al. (2001). The caveat is that the present distance estimate is not strictly an independent empirical estimate.

The second method is the empirical, Cepheid-independent one suggested by Lee et al. (1993). Summarized by SC98 (p. 168), it is based on the relation between the (dereddened) $I$-band distance modulus and $I_0,TRGB$, i.e., $(m-M)_0 = I_{0,TRGB} + BC_I$. The $I$-band bolometric correction, $BC_I$, is determined using

$$BC_I = [0.881 - 0.243(V-I)_{0,TRGB}] \pm 0.057 \text{ mag} \tag{2}$$

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### Table 3: Distance-Related Information for NGC 300

| Field (arcmin) | $I_{TRGB}$ (mag) | $M_{I,TRGB}$ $\pm r \pm s$ (mag) | $A_V$ (mag) | $A_I$ (mag) | $(m-M)_0$ $\pm r \pm s$ |
|---------------|-----------------|----------------------------------|------------|------------|-----------------|
| F1 ............. | 22.52 ± 0.02    | -4.06 ± 0.07 ± 0.13$^a$          | 0.039      | 0.019      | 26.56 ± 0.07 ± 0.13 |

Note.— Col. (1): Radial distance of WFPC2 field from galaxy centre. Col. (2): Tip $I$-band magnitude of the RGB. Col. (3): Absolute $I$-band magnitude of the RGB tip. Cols. (4) and (5): Galactic foreground extinction (Schlegel, Finkbeiner, & Davis 1998) converted to $I$-band using the Cardelli, Clayton, & Mathis (1989) extinction law and $R_V = 3.1$ (NED). Col (6): Distance modulus.

$^a$ Ferrarese et al. (2000), with $r$ = random and $s$ = systematic.
from Da Costa & Armandroff (1990), where \((V-I)_{0,\text{TRGB}}\) is the
(dereddened) color of the RGB locus at the tip magnitude. The
magnitude \(M_{\text{bol,TRGB}}\) is determined using
\[
M_{\text{bol,TRGB}} = -0.19[\text{Fe/H}] - 3.81, \tag{3}
\]
and \([\text{Fe/H}]\) of the parent stellar population is related to the
(dereddened) color of the RGB locus at \(M_I = -3.5(V-I)_{0,-3.5}\) via
\[
[\text{Fe/H}] = -12.64 + 12.6(V-I)_{0,-3.5} - 3.33(V-I)_{0,-3.5}^2, \tag{4}
\]
both from Lee et al. (1993). With \((V-I)_{0,\text{TRGB}} = 1.82 \pm 0.1 \text{ mag}^2\) and \((V-I)_{0,-3.5} = 1.58 \text{ mag}\) (field F1), we find
\([\text{Fe/H}] = -1.05 \text{ dex}\) and \((m - M)_0 = 26.62 \pm 0.06 \text{ (random;}
from I_{\text{TRGB}}\) is in good agreement with the Cepheid-based
calibration.

In the third method, we calculated \(M_{\text{I,TRGB}}\) using the
theoretical calibration of SC98; the recipe makes use of their
recalibrated relation between the global metal-to-hydrogen
ratio \([\text{M/H}]\) and \((V-I)_{0,-3.5}\):
\[
[M/H] = -39.270 + 64.687(V-I)_{0,-3.5} - 36.351(V-I)_{0,-3.5}^2 + 6.838(V-I)_{0,-3.5}^3, \tag{5}
\]
The SC98 recipe is based on updated stellar models, the empirical
calibration of synthetic colors, and the adopted bolometric
correction. They obtained the following relation for the absolute
I-band magnitude of the TRGB:
\[
M_{\text{I,TRGB}} = -3.953 + 0.437[M/H] + 0.147[M/H]^2, \tag{6}
\]
which leads to \([M/H] = -0.85 \text{ dex, and}\) \((m - M)_0 = 26.73 \pm
0.06 \text{ mag (random). The difference between this value and the value from the Cepheid calibration (i.e., 26.56 mag; Freedman et al. 2001) is 0.17 mag.}

The good agreement of the first method (empirical TRGB
calibration of the distance tied to the Cepheid scale; F00) with the
Cepheid distance itself is not surprising. The TRGB distance
from the Lee et al. (1993) calibration is an independent
measure of the distance to NGC 300 and is in good agreement
with the F00 measurement. There is, however, a discrepancy
with the theoretical calibration of SC98, which may be a zero-
point problem.\(^5\) In conclusion, we adopt the F00 value of
\(M_{\text{I,TRGB}}\), because it is precise and especially because it is a
statistically averaged solution whose zero point derivation is
based on a homogeneous and consistent calibration. The
corresponding distance modulus estimate is given in Table 3.

5. INTERNAL EXTINCTION IN NGC 300

For our study of the bright stellar populations of NGC 300,
it is very important to consider the issue of internal reddening
of the galaxy, because it can broaden CMD features: internal
extinction may vary locally depending on the spatial distribution
of dust and stars (e.g., Jansen et al. 1994). It is probably
low on average, based on the dust maps of SFD98, which are

in fact in good agreement with the values from the lower
resolution dust maps of BH82 mentioned in § 4. Going one
step further, we looked for a difference in extinction between
the F1 and F3 fields. From § 4, we know that the TRGB
magnitudes in these fields appear to differ by not more than
about 0.1 mag at most, which argues against significant differ-
ential extinction in these fields. This is especially mean-
ingful because the I-band TRGB magnitude is fairly insensitive
to variations in heavy element content (e.g., Salaris, Cassisi, &
Weiss 2002), something that could partially mimic differential
extinction.

Another issue is extinction in the nuclear region of NGC 300.
Indeed, although NGC 300 is near face-on, as opposed to the
edge-on case, for which central extinction tends to be higher,
there is the possibility of significant extinction in the central region (Peletier et al. 1995). In contrast to the other fields, there are clear shells of dust in the central region based on visual inspection of the ESO/WFI (real-) three-color image\(^7\) (Fig. 1). These shells are distributed in a fragmented,
ringlike structure of deprojected diameter \(\sim 1.2 \text{ kpc} (\sim 1',\)
with an annular thickness of \(0.2-0.4 \text{ kpc} (\sim 10^{-2}-20'),\)
based on visual inspection. The dust ring appears to be symmetric
about the bright compact central object studied recently by
Böker et al. (2002). Significantly, there is a stark absence of
blue colors in the image, which suggests that there may be
significant extinction, possibly hiding evidence of recent star
formation, and/or that there has been relatively little recent star
formation in the nuclear and circumnuclear region. For the
central region, Davidge (1998) found evidence to support the
idea of suppression of recent star formation, a plausible result
because the study was based on essentially extinction-free
near-IR imaging.

Finally, we remark that almost no reddening has been
reported for two early-type supergiants, one near the galaxy
center (at \(r \sim 0.55\)) and one in the outskirts (at \(r \sim 9.16\)
(Urbanaja et al. 2002). However, it is very difficult to make
specific conclusions regarding field-to-field differences in
extinction from such a sparse sample, and a larger sample is
needed in order to place wide-field spectroscopy-based red-
dening information on a firm statistical footing.

6. THE YOUNG STELLAR POPULATION

We checked whether there are any spatially distinct stellar
groups or associations of stars younger than about 1 Gyr in the
F1 and F3 fields at \(I < 24 \text{ mag}\) (i.e., an extension of box A in
Fig. 4). For this, a histogram of the number density of stars in
100 pixel–wide columns was then computed. In each histo-
gram, a background and 4 \(\sigma\) detection threshold level was
determined from the first 750 columns of the WFPC2 frame.
In this way, any detection is affected neither by the WFPC2
L shape, shown in Figure 5 nor by statistical fluctuations.
While there is no real evidence for a stellar group in the F3
field, there is a significant group in the other field (F1). For
validation of the detection, we varied the bin size from 50 to
150 pixels, and the significance remains. Based on a Gaussian
fit to the histogram for field F1, we find the size (FWHM) to
be about 140 pc at a distance of 2.02 \pm 0.07 Mpc (e.g.,
Freedman et al. 2001), which is consistent with the average
OB association size in NGC 300 (Pietrzyński et al. 2001).
Based on the work of Kim et al. (2002), who age-dated 15% of
the 117 OB associations cataloged by Pietrzyński et al.

\(^7\) A high-resolution color image is included in the online electronic version.
(2001), the newly detected association would have an age on the order of 10 Myr or less and is approximately of average size. Accordingly, bright main-sequence and/or blue supergiant stars may be present. We note that none of the X-ray sources detected by the ROSAT HRI (Read & Pietsch 2001) occur in the F1 field or in the other fields. The coordinates of the association are given in Table 4.

Another issue is star-forming environments. The F1 field covers parts of a major and minor spiral arm (see Figs. 1 and 5, bottom). The blueness of these arms with respect to the interarm region argues for a rich supply of young stars at the southern end of the F1 field, which is also indicated by Figure 5 (top). Consequently, it is not surprising that there are parts of OB associations cataloged by Pietrzyński et al. (2001), namely AS 054 and AS 055, at the southern end of the WFPC2 field of view (Fig. 5). We note that of the Wolf-Rayet stars found by the Schild et al. (2003) survey of several fields and the associations of OB stars cataloged by Pietrzyński et al. (2001), a few such stars occur in our fields but did not meet our selection criteria (see § 2, i.e., rejected as saturated, stellar blends, and/or large fitting/photometry errors) and have been ignored.

Pursuing the SF issue further, we refer to cataloged blue stars, OB associations, and the correlation made with H ii maps by Pietrzyński et al. (2001). From their Figure 4, we see that there is a significant dropoff in the number of OB associations at $r \sim 9'-12'$ (projected). Consequently, if these were used as tracers of star formation, one would conclude that such activity is significantly lower at large radii with respect to that of the disk. We also note that there are some blue stars at $r = 12'-13.5'$ that might be tracing the galaxy out to even larger radii, or possibly associated with parts of tidal streams, but we cannot exclude the possibility that such stars are simply just the bright field star population that one expects (see § 7).

The next issue is the amount of recent star formation. Based on the presence of blue helium-burning stars in Figure 8, a marked recent burst of star formation in the observed fields is likely. However, the small WFPC2 field of view certainly means that the brightest population of stars may not have been sampled adequately. Nevertheless, we can say that star formation may well be continuing at the observed pointing, statistically speaking, based on the presence of a blue plume stretching up to $V \sim 18$ mag ($I \sim 18$ mag also) in the ($V, B-V$) CMD of Pietrzyński et al. (2001), which covers the whole galaxy. Such stars may be in OB associations or in less concentrated star-forming regions. Guided by the isochrones in the same figure, we also see clues that there may have been

Table 4

| $\alpha$ (J2000.0) | $\delta$ (J2000.0) | FWHM (pc) |
|------------------|------------------|-----------|
| 00 54 56.6........ | −37 35 25.0      | 130–145   |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Coordinates are taken from the online Aladin sky atlas; position error is estimated to be 10"–20".

Fig. 8.—CMD for NGC 300 F1 and F3 fields. The stellar evolution tracks/isochrones for the adopted $Z = 0.004$ Padova models (see text) are plotted in the left panel (thin solid lines). These are labeled with the starting mass in solar units and with corresponding ages. The age – $I$-band magnitude trend for blue supergiant/core helium burning stars is marked in the right panel for two metallicities, namely $Z = 0.003$ (diamonds) and 0.005 (triangles), and age error sizes are smaller than the symbol sizes. From metal-rich (right) to metal poor (left), reddened ridgelines (thick solid lines) are for 47 Tuc, $[\text{Fe/H}] = −0.71$, NGC 1851, $[\text{Fe/H}] = −1.29$, and NGC 6397, $[\text{Fe/H}] = −1.91$. The adopted true distance modulus is 26.5 mag. The 90% completeness limit is also indicated (dashed lines).
very recent star formation, because of some bright, possibly zero-age main sequence stars at \( V-I \sim -0.4 \) mag that are present.

Finally, there is evidence for a difference in the stellar content of the fields F1 and F3. One can see that there is a relative dearth of intermediate-mass stars in the range 5–12 \( M_\odot \) in the F3 field with respect to the F1 field; such stars in the F1 field are predominantly associated with the spiral arms (see Fig. 5). We recall from §3 that the ratio of old to young (\( \leq 1 \) Gyr) stars for the two fields are not in good agreement (see Table 2), and so the observation cannot be attributed completely to the difference in surface brightness (or the mean star formation activity) between two disk fields (see §3). It can be attributed to the significant difference in the star formation rate at these locations in NGC 300, as shown in §8 and Figure 10.

7. STAR FORMATION HISTORY

In each of the two fields at intermediate radii (F1 and F3), one finds that only the brightest stars have been detected. Accordingly, the associated CMDs do not permit a detailed derivation of the star formation history (SFH) using synthetic CMDs. Despite this, we can broadly estimate how the heavy-element abundances and star formation rate (SFR) has changed during the lifetime of NGC 300. We have followed the method and have adopted the hypotheses introduced by Aparicio, Gallart, & Bertelli (1997) and Martínez-Delgado, Aparicio, & Gallart (1999). We refer the reader to these papers for a detailed description of the method. However, a brief summary here is appropriate.

In short, the SFH is considered to be composed of three functions: the SFR \( \psi(t) \); the initial mass function (IMF); and the chemical enrichment law \( Z(t) \). With these functions as input, the synthetic CMDs were computed using scripts introduced by Aparicio et al. (1997). For the analysis, we have assumed a Salpeter IMF (Salpeter 1955) with low and high mass cutoffs at 0.7 and 30 \( M_\odot \), respectively, and have ignored the possible effects of binary stars, because the old population in our CMD is mainly composed by RGB and AGB stars. Such stars are expected to be well mixed in the disk by the present time: with a random velocity of 1 km s\(^{-1}\), the crossing time for a 1.5 kpc region, or the WFPC2 field size, would be about 1.5 Gyr. Consequently, \( Z(t) \) and the SFR have been determined for each WFPC2 field rather than for the individual chips in order to maximize the signal-to-noise ratio.

To determine \( Z(t) \), we considered five age intervals with widths suited to the present use of \( V \) and \( I \)-band photometry, which is relatively insensitive to variations in \( Z(t) \). These intervals are 15–12, 12–9, 9–6, 6–3, and 3–1 Gyr. For each age interval, we adopted a constant SFR and synthesized a stellar population of 40,000 stars with absolute magnitudes brighter than \( M_I = -3.0 \) mag. The chemical abundance \( Z \) of each star has been taken at random. Internal photometric errors from the artificial star tests described in §2 have been included.

In order to estimate the mean heavy-element (\( Z \)) abundances of each age interval, we adopted the following recipe. Firstly, we selected stars from the synthesized population of stars with heavy-element abundances in an arbitrary range \( (Z_1 - Z_2) \). Then we measured the position and full width of the synthetic RGB/AGB locus for stars at 22.55 < \( I \) < 26 and \( V-I > 1.4 \) mag. This procedure was repeated a few hundred times for different \( Z \) ranges. From the resultant database, only those \( Z \) pairs giving synthetic colors and widths that closely matched the values from the real CMD data were chosen. In this way we could obtain an estimate of the maximum and minimum \( Z \) values in each age interval that are consistent with the real CMD data. The two \( Z \) indicators (width and position of the RGB/AGB locus), however, sometimes returned different \( Z \) pairs; the standard deviation of the differences is taken as an estimate of the uncertainty in \( Z(t) \), which is plotted in Figure 9. For a test of the robustness of this \( Z(t) \) solution to the selected CMD area defined above, we varied the \( I \)-band range and color boundary by up to 0.1 mag. The variation in \( Z \) is of the order of 20%, which is consistent with the largest error bar size.

For the past 1 Gyr, our only estimate of the mean \( Z \) abundance comes from spectroscopy of two blue supergiants outside the central region (\( r \geq 2.3 \)) of NGC 300 (Bresolin et al. 2002b; Urban et al. 2002). We take the average and rms of these and included them in Figure 9. It turns out that extrapolation of \( Z(t) \) to ages less than 1 Gyr leads to a final agreement with the empirical estimates, but ongoing (e.g., Bresolin et al. 2002b) and future spectroscopic studies are needed for better global \( Z \) information on NGC 300.

Next, we computed a synthetic CMD for a stellar population with ages in a narrow interval using a library of stellar evolution tracks (Bertelli et al. 1994). We call this a partial CMD: taking a set of partial CMDs, each covering different age intervals (e.g., several times \( 10^8 \) yr to a few times \( 10^9 \) yr), the full galaxy age (\( \sim 15 \) Gyr) is accounted for. A combination of partial CMDs that covers the full age of the galaxy is called a candidate global synthetic CMD.

For each real CMD, we computed a total of 50,000 candidate global synthetic CMDs in the following way. Each such CMD was made by simply extracting all stars from the synthesized stellar population (mentioned earlier), such that in each age interval, there are only stars of the right age and

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The CMD may not be used mainly because of the lack of a relatively Z-sensitive feature for stellar ages below about 1 Gyr, e.g., Fig. 8 (right).

Shorter age intervals were adopted for the past 6 Gyr than for the \( Z(t) \) estimate (see Fig. 9), because time resolution is potentially much better for SFR calculations than that of \( Z \) over the past few \( 	imes 10^7 \) yr, especially if dramatic SFR changes could have occurred (e.g., see Williams 2002). Interpolation was used to assign minimum and maximum \( Z \) values to the shorter age bins at ages greater than 1 Gyr.
each star has a synthesized Z value between the estimated maximum and minimum value for that age interval. In the next step, we selected 11 relatively age-sensitive CMD boxes that sample the main features of the real CMD and counted the stars in those boxes (see Fig. 4). To paraphrase Aparicio et al. (1997), let us label the number of stars in box \(j\) of the observed CMD as \(N^o_j\), and the number of stars in box \(j\) of the partial CMD \(i\) as \(N^m_{ji}\) (the partial CMD of the \(i\)th age interval). The variable \(m\) is the total number of candidate synthetic CMDs generated. The star counts per box are related to each other by

\[
N^m_j = k \sum_i \alpha_i N^m_{ji},
\]

where \(\alpha_i\) is the linear combination coefficient in age interval \(i\) and \(k\) is a constant scaling factor. The coefficient \(\alpha_i\) and \(k\) are related to the SFR \(\psi(t)\) by

\[
\psi(t) = k \sum_i \alpha_i \psi_i \Delta_i(t),
\]

where \(\Delta_i(t) = 1\) if \(t\) is inside the current age interval of interest (corresponding to the partial model \(i\) or similarly the model associated with the age interval \(i\) and \(\Delta_i(t) = 0\) otherwise (Aparicio, Carrera, & Martínez-Delgado 2001), and \(\psi_i\) corresponds to the partial model \(i\). The \(\psi(t)\) values having the highest probability of fitting the data in a \(\chi^2\) sense\(^\text{10}\) can be obtained by a least-squares fitting of \(N^m_j\) (i.e., simulated star counts) to \(N^o_j\) (i.e., observed or real star counts), where the \(\alpha_i\) coefficients are the free parameters and each is chosen randomly in the range 0 to 1. Coefficients that provide synthetic CMDs that best match the real CMD will have the smallest \(\chi^2\) values. Accordingly, after producing 50,000 sets of coefficients (i.e., 50,000 candidate SFR solutions),\(^\text{11}\) one has a distribution of \(\chi^2\) values. The wide spread actually occurs because there are no unique age indicators for each age interval in our CMDs; indeed, none are expected because of the large degeneracy between age and chemical composition in our data.\(^\text{12}\) Thus, we take the standard approach of taking the average of the best solutions, with their standard deviation; here, we define the best solutions as those meeting a \(\chi^2\) cutoff criterion. This criterion is \([\chi^2 < (\chi^2 - 3\sigma)]\), where \(\sigma\) is the standard deviation in the \(\chi^2\) distribution. With this, a few hundred SFR solutions or less \(^{\text{11}}\) (Fig. 11) for comparison with the real CMDs (see Fig. 8); photometry uncertainties in the real data have been simulated and added. Overall, there is good agreement for each

that the typical error-bar size indicates an uncertainty factor of about 2–3 in the SFR in general; that is consistent with the uncertainties presented in previous studies that considered the upper RGB and several age intervals between 15 Gyr and now (e.g., Aparicio et al. 1997, their Fig. 8, LGS 3; Dolphin 2002, his Fig. 7e, simulated galaxy with a relatively complex SFH). It is evident that error size in Figure 10 tends to grow toward younger ages; on one hand, this is due to the decreasing number of recently formed stars in the observed fields, which forces the use of wide age intervals for adequate signal-to-noise ratios, while on the other hand, there might well have been episodic star formation during the past few \(\times 10^9\) yr to which our age binning is possibly fairly insensitive.\(^\text{13}\)

Another concern points the ability to estimate both \(Z(t)\) and SFH\((t)\) from RGB and AGB star data alone, as opposed to also having data on the horizontal branch and fainter structure. The concern stems from the difficulty of disentangling the contribution of age and chemical composition to stellar color, the so-called degeneracy between the two parameters. Thus, in such a situation, solving simultaneously for the true \(Z(t)\) and SFR\((t)\) is difficult, even if possible, as the reasoning is flawed. The approach that we have applied is, however, one solution to this problem. We recall that the approach that we have adopted has been to first assume a constant SFH and then to solve for \(Z(t)\). This \(Z(t)\) is then used as input to obtain the solution for SFR\((t)\). Given the uncertainties in the final \(Z(t)\) and SFH\((t)\), the approach we have followed is deemed to be tolerable. We also conclude that although a detailed chronology of star formation in the WFPC2 fields over the past few \(\times 10^9\) yr is beyond the scope of the present paper, we can form broadly acceptable conclusions regarding star formation (SF) activity. We discuss this issue in \(\S\) 8.

In order to test the reliability of the derived star formation history, we present the synthetic CMDs derived for the fields (F1 and F3) for which an SFH analysis has been possible (Fig. 11) for comparison with the real CMDs (see Fig. 8); photometry uncertainties in the real data have been simulated and added. Overall, there is good agreement for each

\(^{10}\) \(\chi^2 = \sum_i (N^m_i - N^o_i)/N^o_i\), where \(k\) is the number of candidate solutions.

\(^{11}\) The common SFR zeropoint is determined by knowing the total initial stellar mass of all stars generated while producing the synthesized stellar population.

\(^{12}\) Such degeneracy would be partially broken by a longer color baseline than \(V-I\), e.g., by including suitable near-infrared data. However, star formation histories can be measured accurately when photometry reaches to \(M_V = +2\) mag (Dolphin 2002), or fainter still, to ancient main-sequence turnoff stars.

\(^{13}\) Dolphin (2002; his Figs. 5 and 7) demonstrates this latter point through estimations of the star formation histories of synthetic galaxies with episodic star formation histories.
The main difference is in the color-magnitude spread: synthetic CMDs are inclined to have tighter features than their counterparts in the real astronomical data. This could be due to a range of extinction values for the stars (Williams 2002) that has not been estimated by the stellar population synthesis models. We note the difference in the star count density at red colors $V-I_k$ 3 mag at/near the RGB peak magnitude in the F1 field, for which the effect is pronounced, is not unexpected, because incompleteness becomes significant for such stars. In addition, the required completeness correction increases significantly at faint magnitudes ($I > 23$ mag), which causes significant scatter in the real data.

8. DISCUSSION: STAR FORMATION

In §7, we determined a low–time resolution chemical enrichment law and SFR(t) for two disk fields in NGC 300. In this section, we summarize briefly the key findings about the SFH of NGC 300, based on WFPC2 data.

The metallicity has been measured in two disk fields to be on average less than 0.006 (or $0.33 Z_\odot$) during the lifetime of NGC 300 and, based on the available evidence, $Z(t)$ appears to have changed relatively little during that time. The present-day value of $Z$ may be of the order of 0.0035–0.0055 based on two empirical (spectroscopic) estimates from Urbanja et al. (2003). Their best-fit oxygen abundance $(12 + \log (\text{O/H}))$ estimates for two blue supergiants are 8.3 and 8.65 dex (their Table 1). We note that Pagel et al. (1979) measured oxygen abundances in six H ii regions in NGC 300. They found oxygen abundances of approximately 8.6–9 dex. It is encouraging that the oxygen abundances from the two spectroscopy studies roughly agree; this fact strengthens confidence in our derived values of $Z$ for the past few $10^8$ yr.

For the star formation rate in disk fields F1 and F3, a simple estimate has been made (Fig. 10) that the derived mean SF rates are 0.002 and 0.04 $M_\odot$ yr$^{-1}$ in the F3 and F1 fields, respectively. We note that the apparent SFR increase at about 100–200 Myr may not be real because of the estimated uncertainty; the occurrence of this feature could reflect a common systematic error for both fields, possibly due to the small-number statistics available for such young stars, which is not assessed by the $\chi^2$ tests. The mean SF densities $\dot{\Psi}/A$ are $3 \times 10^{-4}$ and $6 \times 10^{-3} M_\odot$ yr$^{-1}$ kpc$^{-2}$ in the F3 and F1 fields, respectively. These SF density values are consistent with expectations for spiral disks: the SFR density in spiral disks can be up to about $0.1 M_\odot$ yr$^{-1}$ kpc$^{-2}$ in spiral disks, and typical activity exhibits a steady-state behavior (Kennicutt 1998). Star formation in nearby spirals has, on average, a strong dependence on galaxy type, weak or no dependence on spiral structure or the presence of a bar, and moderate dependence on past interactions (Kennicutt 1998). It may well be that the average SF activity in the NGC 300 disk follows the typical trend in nearby spiral disks, but conclusive evidence will only be obtained from future observations of more of the galaxy.

On the other hand, Davidge (1998) reported a suppression of recent star formation in the central region of NGC 300 based on near-IR observations. In our completeness-corrected $I$-band luminosity functions for stars younger than a few times $10^8$ yr (at $V-I < 0.6$ mag) and brighter than the 50% completeness limits, we also find a significant cutoff in the central function with respect to the F1 and F3 fields (Fig. 12). However, as mentioned in §5, the central extinction is unknown and may be significant: from the ESO/WFI image, there is evidence for distinct dust shells in part of the F1 field-of-view that are superimposed on a much more widely spread dust cloud. Consequently, internal extinction could possibly...
explain the truncation of the central $I$-band luminosity function: about 1–2 mag of $I$-band extinction would be needed in order to dim the brightest object observed in the outer fields ($I \sim 18$ mag) to match the brightest stars in the central field (Fig. 3). Finally, central ringlike gas (but also dust) structures are expected based on simulations of the detailed chemical and dynamical evolution of galaxies (e.g., Samland & Gerhard 2003).

Another issue is that there has been an increase in SFR over the last few Gyr in NGC 300. We know that the observed increase in SF activity in the F1 and F3 disk fields is not unprecedented in some spiral galaxy studies; some sites in M31 have SF rates indicating that sufficient gas may have been retained and/or acquired for episodic or secular star formation (Williams 2002, 2003, based on the SFR measured in OB associations).

Finally, there is the issue of why there has been relatively little increase in Z over time in NGC 300 and why it appears not to have changed significantly over the lifetime of the galaxy. Possibly, metal-poor gas has been acquired by NGC 300. In the context of metal-poor gas acquisition through past encounters, we note that intergalactic gas and stars may be a partial signature of such encounters: a clustering of H I clouds around NGC 300 and NGC 55 was found by Haynes & Roberts (1979) based on sensitive 21 cm observations, but uncertainty over group membership of these clouds remains (Haynes & Roberts 1979). We also note that color gradients and morphological studies of spiral galaxies can reveal clues about past mergers: no evidence for a color gradient in NGC 300 was found by C85, and a detailed study of the morphology of NGC 300 (e.g., examining distorted isophotes hinted at in Fig. 1) remains to be tackled.

9. CONCLUSIONS

We have presented the first WFPC2 $V$ and $I$ photometry for the Sculptor Group late-type spiral galaxy NGC 300 in four fields ranging from the center to the outer edge. In particular, we make the following conclusions.

1. We have derived the first estimate of the star formation history in two disk fields. Our analysis indicates that stars were born at similar epochs and that star formation activity possibly increased on average over time, but at different mean rates.

2. The main stellar population is predominantly old, consisting of RGB and AGB stars, based on a synthetic CMD analysis. The metallicity $Z$ is less than 0.006 (or 0.33 $Z_\odot$), with no evidence for significant change in mean $Z$ over time in both disk fields.

3. In the circumnuclear region, we find a dearth of bright stars relative to two disk fields that cannot be explained by observational effects. Taken at face value, this finding would agree with the Davidge (1998) report of suppressed star formation there during the past $10^9$ yr, but the possibility of significant central $I$-band extinction (up to about 1–2 mag) remains.

4. We have also reported a newly detected young star association (probably up to ~10 Myr old) of about average size (~140 pc) in one of the disk fields that probably coincides with a star-forming region.

5. Finally, using Ferrarese et al. (2000) Cepheid-based calibration, the distance modulus has been determined from the tip magnitude of the RGB to be $(m - M)_0 = 26.56 \pm 0.07$ ($\pm 0.13$) mag. This is in good agreement with the Cepheid distance to NGC 300 from Freedman et al. (2001). Incidentally, both values are in good agreement with the TRGB distance estimated using the Lee et al. (1993) empirical calibration, which is Cepheid independent. There is, however, a discrepancy with the theoretical calibration of the RGB tip magnitude from SC98, which may be a zero-point problem. Accordingly, this means that the same difference in magnitude between the Cepheid distance and the theoretical calibration of the distance for NGC 300 exists for galaxies in the HST key project on the extragalactic distance scale.

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Fig. 12.—Four WFPC2 field $I$-band luminosity functions, corrected for incompleteness, for stars above the 50% completeness threshold with $V - I < 0.6$ mag. These fields are F1 (dotted line), F2 (solid line), F3 (dashed line), and F4 (dot-dashed line). Error bars are $\pm \langle N \rangle^{1/2}$. See § 8 for further details.
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