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Published in:
The Astronomical Journal

DOI:
[10.1086/300515](https://doi.org/10.1086/300515)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
1998

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Tolstoy, E., Gallagher, J. S., Cole, A. A., Hoessel, J. G., Saha, A., Dohm-Palmer, R. C., Skillman, E. D., Mateo, M., & Hurley-Keller, D. (1998). Wide Field Planetary Camera 2 Observations of Leo: A Predominantly Young Galaxy within the Local Group. *The Astronomical Journal*, 116(3), 1244-1262. <https://doi.org/10.1086/300515>

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WIDE FIELD PLANETARY CAMERA 2 OBSERVATIONS OF LEO A: A PREDOMINANTLY YOUNG GALAXY WITHIN THE LOCAL GROUP¹

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Received 1998 April 14; revised 1998 May 18

ABSTRACT

The unprecedented detail of the Wide Field Planetary Camera 2 (WFPC2) color-magnitude diagrams (CMDs) of the resolved stellar population of Leo A presented here allows us to determine a new distance and an accurate star formation history for this extremely metal-poor Local Group dwarf irregular galaxy. From the position of the red clump, the helium-burning blue loops, and the tip of the red giant branch, we obtain a distance modulus, $m - M = 24.2 \pm 0.2$, or 690 ± 60 kpc, which places Leo A firmly within the Local Group. Our interpretation of these features in the WFPC2 CMDs at this new distance based upon extremely low-metallicity ($Z = 0.0004$) theoretical stellar evolution models suggests that this galaxy is predominantly young, i.e., less than 2 Gyr old. A major episode of star formation 900–1500 Gyr ago can explain the red clump luminosity and also fits in with our interpretation of the number of anomalous Cepheid variable stars seen in this galaxy. We cannot rule out the presence of an older, underlying globular cluster age stellar population with these data. However, using the currently available stellar evolution models, it would appear that such an older population is limited to no more than 10% of the total star formation to have occurred in this galaxy. Leo A provides a nearby laboratory for studying young metal-poor stars and investigations of metal-poor galaxy evolution, such as is supposed to occur for larger systems at intermediate and high redshifts.

Key words: galaxies: irregular — Local Group — color-magnitude diagrams — galaxies: stellar content — stars: distances

1. INTRODUCTION

Small galaxies are common and apparently structurally simple. They may provide an important perspective on how luminous structures have evolved in the universe. Despite a variety of theoretical models (e.g., Dekel & Silk 1986; Hensler & Burkert 1990), we cannot predict how even the simplest galaxies have changed over time. In particular, the internal clocks that set the time interval for major star formation are seen to be highly variable in the Galactic retinue of dwarf spheroidals (dSphs), ranging from ancient systems where star formation was complete 10 Gyr ago to galaxies that are mainly of intermediate age (e.g., van den Bergh 1994). The presence of numerous small, actively star-forming field galaxies at moderate redshifts of $0.3 < z < 1$ suggests that such asynchronous behavior may be the rule rather than the exception among smaller galaxies (e.g., Babul & Ferguson 1996).

However, it still remains to be understood exactly what are faint blue galaxies (FBGs) that are found in deep

imaging surveys (e.g., Ellis 1997). Their sheer numbers make them a cosmologically significant population and an important tracer of the star formation history (SFH) of the universe. There is considerable evidence that these FBGs are predominantly intermediate-redshift ($z < 1$, or a look-back time out to roughly half a Hubble time), late-type, intrinsically *small* galaxies undergoing strong bursts of star formation (e.g., Glazebrook et al. 1996; Lilly et al. 1996; Odewahn et al. 1996). The best way to understand FBGs is to discover their nearby counterparts, which we can study in detail, and directly observe the absence or presence of past bursts in color-magnitude diagrams (CMDs). Irregular galaxies are very strong candidates for what is left of the FBGs in our nearby universe. They are systems that may have undergone one or more bursts of star formation in the last few gigayears (Matteucci & Tosi 1985). They exist in numbers large enough that, could they be made bright enough for a short time in the past, they could easily account for the population of FBGs (e.g., Babul & Ferguson 1996).

It is still an open question as to why dwarf galaxies in the Local Group display such a wide range in stellar age distributions. In our sample (Skillman 1998) we are finding enhanced star formation rates (SFRs) over gigayear timescales, during which the bulk of the stellar populations within small galaxies are formed, rather than very short

¹ Based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under NASA contract NAS 5-26555.

discrete bursts ($\lesssim$ a few $\times 10^7$ yr). The physical mechanisms responsible for this behavior are uncertain. Current theoretical models mainly consider cases where SFR is tied to the gas supply. Epochs of active star formation can then occur either due to delayed cooling of gas associated with a small galaxy (e.g., Kepner, Babul, & Spergel 1997; Spaans & Norman 1997) or through rejuvenation of a preexisting small galaxy due to gas capture within a galaxy group (e.g., Silk, Wyse, & Shields 1987). Another possibility is that dwarfs were formed from tidal debris produced by interactions between galaxies in the Local Group, although it is not clear what objects could have spawned the Leo I and considerably more distant Leo A dwarfs (e.g., Hunsburger, Charlton, & Zaritsky 1996).

Here we present the results for Leo A (= DDO 69, Leo III, UGC 5364), a nearby Magellanic dwarf irregular galaxy. A variety of studies have given this galaxy a large range of possible distances (e.g., Hoessel et al. 1994, hereafter H94, and references therein). There are several faint H II regions distributed along the ridge of highest column density H I (Tolstoy 1996; Hunter, Hawley, & Gallagher 1993), which provide a very low limit to the current SFR (over the last 10 Myr) of less than $10^{-4} M_{\odot} \text{ yr}^{-1}$. The brightest H α emission in the galaxy comes from a planetary nebula, which yields an extremely low oxygen abundance of $\sim 2.4\%$ solar (Skillman et al. 1989).

Recent H I observations (Young & Lo 1996) show that the optical galaxy is surrounded by a large H I halo, extending out ~ 3 times the optical diameter at a column density of $4 \times 10^{19} \text{ cm}^{-2}$. The detected H I flux corresponds to an H I mass of $(8.1 \pm 1.5) \times 10^7 M_{\odot}$, of which $\sim 30\%$ is in the halo at column densities below $2 \times 10^{20} \text{ cm}^{-2}$. The observed H I velocity gradient across Leo A in H I is so small that the changes in the velocity dispersion most likely reflect the conditions in the interstellar medium (ISM) rather than rotation or velocity crowding effects. These H I observations show that the physical state of the ISM in Leo A is surprisingly similar to that in other, larger, more metal-rich galaxies (including our own), despite the fact that Leo A is dominated by internal motions with very little effect coming from the exceedingly low global rotation measures.

The resolved stellar population of Leo A has been studied before by Tolstoy (1996) in the Thuan-Gunn filter system. It was concluded that the SFR in the galaxy must have been higher in past than at the present time by a factor of ~ 3 , although the interpretation only went back ~ 1 Gyr because of the limitations of crowding and sensitivity of the ground-based images. This study adopted the distance as determined by H94. Our present observations favor a much smaller distance (see § 3.1), which has significant impact on the interpretation of the CMD. The crowding in the ground based images resulted in the red giant branch (RGB) population being misidentified as the red super giant (RSG) population.

Here we show how the details of the SFH of the last few gigayears obtained from uncrowded WFPC2 imaging helps us understand the properties of this galaxy and why we believe the variable stars that H94 identified are in fact W Virginis (W Vir) or anomalous Cepheid (AC) variable stars.

2. OBSERVATIONS

The *Hubble Space Telescope* (HST) data in this paper comes from the Wide Field Planetary Camera 2 (WFPC2) using only four orbits per galaxy to obtain observations in

three filters for a sample of nearby dwarf irregular galaxies (Skillman 1998). The sample consists of Sextans A, Pegasus, Leo A, and GR 8. The results have been quite dramatic and illustrate the tremendous advances possible even with short exposures when the problems of crowding have been virtually illuminated (Dohm-Palmer et al. 1997a, 1997b, 1998; Tolstoy 1998; Gallagher et al. 1998).

Our data consist of HST WFPC2 images, which cover the majority of the central region of this small galaxy (see Fig. 1). There are three exposures in the F555W (*V*) and F814W (*I*) filters (3×600 s) and four exposures in the F439W (*B*) filter (2×900 s and 2×1100 s). Each image is offset by a few pixels plus a fractional pixel offset, or “dithered” with respect to each other in an attempt to compensate for the under-sampled point-spread function (PSF) (Fruchter & Hook 1996) and the intrapixel sensitivity variations (Biretta et al. 1996, p. 91). The images in each filter were combined by reregistering each image to nearest integer pixel; they were then cosmic-ray-cleaned and combined using techniques described by Saha et al. (1996b). The resulting highly resolved WFPC2 images of the heart of Leo A are shown in Figure 2. We did not make use of the drizzle techniques because there were too few separate frames and it was unclear what the noise properties, and hence the photometric fidelity, of the final images would be (see discussion in Dohm-Palmer et al. 1997a).

Ground-based images were also taken with the Michigan-Dartmouth-MIT (MDM) Hiltner 2.5 m telescope on Kitt Peak for calibration check on the HST *V* and *I* magnitudes. The *V* (600 s) and *I* (600 s) images were taken on 1998 January 23, in photometric conditions and $0''.9$ seeing. The *I* calibration used 30 stars, and the fit rms was 0.013 mag (the average errors on the standards was 0.004), for *V*–*I* there were 28 stars, and the rms was 0.016 mag. The calibration is reliable at the 2%–3% level, unless something very peculiar occurred for which there is no evidence. These MDM images also cover a much larger area ($9' \times 9'$) than the HST images, and so we are also able to usefully increase the statistics for the brighter stars, such as those on the RGB.

2.1. Color-Magnitude Diagrams

Photometry was carried out using a version of DoPHOT (Schechter, Mateo, & Saha 1993) altered to take account of a variable PSF over each image (Saha et al. 1996b). The HST photometry was calibrated and converted to the “standard” *UBVRI* system using the precepts laid out in Holtzmann et al. (1995). This includes a correction to a $0''.5$ aperture. The aperture correction for each filter and each chip and the accompanying errors are listed in Table 1. Also listed in Table 1 are the zero point (Zpt) and the color terms (T_1 and T_2) used in the photometric solution, which, together with their errors, come from the Holtzmann et al. 1995 paper. Here are the photometric solutions that we applied to our WFPC2 data to calibrate them on the *BVI* standard system:

$$\begin{aligned} B &= -2.5 \log (\text{DN}^{-1}, \text{F439W}) + [T_1(B - V)] \\ &\quad + [T_2(B - V)^2] + \text{Zpt} + 2.5 \log \text{GR}, \\ V &= -2.5 \log (\text{DN}^{-1}, \text{F555W}) + [T_1(V - I)] \\ &\quad + [T_2(V - I)^2] + \text{Zpt} + 2.5 \log \text{GR}, \end{aligned}$$

FIG. 1.—WFPC2 footprint superposed on 15'' square piece of the POSS where Leo A is faintly visible as a smudge in the center. The WFPC2 pointing clearly covers most of the central star-forming region of the galaxy. The H I contours of the total H I map of Young & Lo (1997) covers this whole area. [See the electronic edition of the *Journal* for a color version of this figure.]

$$I = -2.5 \log (\text{DN}^{-1}, \text{F814W}) + [T_1(V-I)] \\ + [T_2(V-I)^2] + \text{Zpt} + 2.5 \log \text{GR} .$$

The T_1 and T_2 terms in the above equations have to be determined iteratively, as the $B-V$ or $V-I$ color of a star is not a priori known. The $+2.5 \log \text{GR}$ is a term applied if the gain is not 14, which is the value for the data that Holtzmann used to determine the photometric solutions. It is $+0.602$ for our observations at gain 7.

TABLE 1
HST PHOTOMETRIC CALIBRATION

Filter	Chip	Aperture Correction	Zpt.	T_1	T_2
B	1(PC)	$+0.04 \pm 0.01$	$+20.070$	$+0.003$	-0.088
	2	$+2.30 \pm 0.03$	± 0.004	± 0.007	± 0.003
	3	$+2.30 \pm 0.02$			
	4	$+2.30 \pm 0.03$			
V	1(PC)	-0.75 ± 0.04	$+21.725$	-0.052	$+0.027$
	2	-0.60 ± 0.02	± 0.002	± 0.007	± 0.002
	3	-0.60 ± 0.02			
	4	-0.58 ± 0.02			
I	1(PC)	$+1.05 \pm 0.03$	$+20.839$	-0.062	$+0.025$
	2	-0.70 ± 0.02	± 0.002	± 0.009	± 0.002
	3	-0.70 ± 0.02			
	4	-0.70 ± 0.02			

The photometry for F814W (I) and F439W (B) images were matched to the F555W (V) photometry, which was the most complete down to the faintest magnitude. The resulting CMDs are presented in Figures 3 and 4 for the individual WFPC2 CCDs and for the combined data in Figures 5 and 6. Figure 7 contains the error distributions that are critical in determining the quality of model fits to these data.

The *HST* CMDs for Leo A contain several distinctive features. There is a red clump (RC) between $23 < M_I < 24$, with $V-I \sim +0.8$. Careful modeling is required to tell if this is truly an “evolved” RC, or if it is wholly, or some mixture with, the base of low-metallicity helium-burning blue loop (BL) stellar tracks. The observed CMD also has a very pronounced BL sequences, as seen in Sextans A (Dohm-Palmer et al. 1997a, 1997b). We cannot rule out the presence of either a red or a blue horizontal branch (HB, BHB). The region expected to be populated by a BHB ($I \sim 24.7$) is completely confused by the young stellar population along the main sequence (MS) and not accurately reached in V , $B-V$.

Looking at Figure 8, it can be seen that the population mixture of the stars in Leo A does not appear to vary significantly with position in the galaxy (also in MDM, see Fig. 9). The young (blue) stars are more centrally clumped, but the RGB population is not a smooth underlying popu-

FIG. 2.—Mosaic of the WFPC2 F555W (V) images of the Leo A dwarf irregular galaxy. The galaxy is highly resolved and transparent. A number of background galaxies can be seen *through* Leo A. Stellar crowding is clearly not a factor in the analysis of these images.

lation as is usually the case (i.e., “Baade’s sheet”) for a very old halo population, it is quite clumpy and not that much more extended out from the center of the galaxy than is the younger population. In the case of Pegasus (Gallagher et al. 1998), there was a clear separation between the predominantly older population in the outer regions (their chip WF3, Fig. 4) and the other chips closer to the center of Pegasus. In Leo A the chip predominantly away from the central regions (WF2) still shows the presence of a MS and BLs, although we have only small number statistics. This suggests that Leo A is a predominantly young galaxy because there has not yet been time for a segregation of different age populations. It is also possible that this segregation becomes less clear at the very low metallicity of Leo A where the reddening of the stellar population due to age is very slow, and thus it is difficult to distinguish an old population (5–10 Gyr) from an intermediate-age population (2–3 Gyr) along the RGB.

2.2. Photometric Calibration Uncertainties of WFPC2 for Leo A

In Figure 10 we show the MDM (I , $V-I$) CMD for the whole field area, which clearly affords a better sampling of the younger brighter populations, such as the RGB, obviously seen in the well-defined tip. We can also see the serious effects of increased crowding in the ground-based

images. The MDM RGB is much broader and bluer than is the *HST* RGB. This is not a broadening of the RGB due to the inclusion of other regions of Leo A with different RGB properties, but an intrinsic feature over the whole ground-based image. We have determined this to be primarily an effect of crowding. Stars at the red edge of the RGB can only be confused with stars that are bluer, hence making the trend of crowding to broaden the RGB in the blueward direction. We checked this by “degrading” *HST* images in V and I and then redoing the photometry. The result is an RGB that is broadened *exclusively* to the red and looks very similar to the MDM CMD in Figure 10.

In Figure 11 we compare the absolute photometry of relatively uncrowded stars in the *HST* with the MDM images. We select stars that have no neighbors within 10 pixels in the *HST* images, and in order that chip-to-chip effects are not a factor, we do this on WF3 only. It could be that there is a systematic offset in color between the *HST* calibration and the ground calibration, although the scatter is large (which could of course be due to problems with either calibration). It is not possible to properly resolve this issue with these data as there are too few stars that are uncrowded in the ground field to match the *HST* data. The simulations described in the preceding paragraph suggest that the offsets we see in Figure 11 are primarily due to crowding in the ground-based images. Thus, despite efforts

FIG. 3.—Observed CMDs for Leo A, plotted by chip for each of the four separate WFPC2 CCDs. We plot V magnitude vs. $B - V$ color. These come from transformations of the F555W and F439W filters. The numbers of stars measured on each chip are printed within each CMD.

to pick only isolated stars, we cannot tell with these data if there is any underlying calibration offset of the WFPC2 versus standard $UBVRI$ photometry.

3. BASIC PROPERTIES OF LEO A

To properly model a CMD it is important to first decide upon the range of values that are acceptable for numerous basic parameters that affect the CMD models. The most significant are the distance, the extinction, and the metallicity distribution of a galaxy. These properties can be determined independently from the CMD, and these independent measures must be consistent with the findings in a CMD. These three basic parameters, in conjunction with observational errors and incompleteness (Tolstoy 1996), make the most significant impact on the properties of the CMD and hence the final SFH model. The basic physical properties of Leo A are summarized in Table 2.

3.1. Distance of Leo A

Unfortunately Leo A does not have a reliable primary distance determination. We compare several different indicators, summarized in Table 3, and describe the properties below.

3.1.1. Variable Stars in Leo A

The distance to Leo A was thought to be well determined from the detection of five δ Cephei variable stars (H94). However, recent observations of δ Cepheids in other galaxies (e.g., Pegasus, Aparicio 1994; IC 10, Saha et al. 1996a)

TABLE 2
GLOBAL PROPERTIES OF LEO A

Property	Value	Reference
$m - M$	24.2 ± 0.2	1
$E(B - V)$	0.02	2
$12 + \log [\text{O}/\text{H}]$	7.3 ± 0.2	3
$(B - V)_T$	0.15 ± -0.2	4
M_B	-11.3	4
$M(\text{H I}) (10^7 M_\odot)$	8.1 ± 1.5	5
$M(\text{H I})/L_B (M_\odot / L_\odot)$	1.3	5

NOTES.—(1) This work; (2) Burstein & Heiles 1984; (3) Skillman et al. 1989; (4) Mateo 1998; (5) Young & Lo 1996.

call into doubt the reliability of using δ Cephei variable stars detected in only one filter. From the WFPC2 CMDs (see Figs. 5 and 6), it is clear that the H94 Leo A distance cannot be correct. There is no way to reconcile either shape

TABLE 3
DISTANCE INDICATORS TO LEO A

Indicator	$m - M$
Cepheid	24.9 ± 0.7
W Vir	24.5 ± 0.5
RGB tip-MDM	24.5 ± 0.2
Red clump (old)	23.9 ± 0.1
Red clump (young)	24.2 ± 0.1
Blue loops	24.1 ± 0.1

FIG. 4.—Same as in Fig. 3, but we plot I magnitude vs. $V-I$ color. These are transformations from F555W and F814W WFPC2 filters. The numbers of stars measured on each chip are printed in each CMD.

of the BLs or the presence of a RC with this large distance. However, all but one of the δ Cepheids identified by H94 in Leo A have roughly the color expected for a bona fide δ Cepheid (Tolstoy 1996), and their light curves closely resemble those expected of δ Cephei variable stars. The Tolstoy

(1996) colors came from observations taken on different nights and so could only be shown to be broadly “red” or “blue.” From these *HST* data it is possible to measure the colors for three Cepheids that happen to fall into the WFPC2 field of view, and the observations were taken

FIG. 5.—Combined CMD of all four WFPC2 chips in V , $B-V$. The number of stars making up this CMD is 2636 stars matched in both filters.

FIG. 6.—Combined CMD of all four WFPC2 chips in I , $V-I$. The number of stars making up this CMD is 7295 stars matched in both filters.

FIG. 7.—DoPHOT-estimated (thus conservative) photometric errors for all the stellar magnitudes in each of the three filters used.

within a few hours of each other (see Table 4). On careful examination it can be seen that in fact two of the Cepheids are on the extreme blue edge of the classical instability strip, and the one that actually falls well within the classical instability strip was found by H94 to be too bright for its period compared with the others and suggested to be an overtone pulsator. Although we do not have a measure of $\langle V \rangle$, the mean magnitude over the light curve, there is only a single V observation for these stars, so there is some uncertainty in where they exactly lie. A possible explanation is that Cepheid (No. 9; H94) is the only bona fide δ Cepheid in the sample, and the other “Cepheids” have colors more compatible with W Vir stars or ACs or are not variables at all. Using only one “classical” δ Cepheid makes the distance determination much less certain because of the intrinsic width of the instability strip (e.g., Tolstoy et al. 1995). However, it does bring the galaxy much closer ($m - M = 24.9 \pm 0.35$), although this value can be off by as much as 0.7 mag in either direction because of the intrinsic width of the instability strip combined with only having a single δ Cepheid.

If we apply the W Vir–period luminosity (PL) relation (which is not very well established, see Appendix A), then we can use the single-epoch WFPC2 V mag to estimate a distance of $m - M \sim 24.5 \pm 0.5$ for Leo A. Despite the uncertainties in both the calibration, and having only one observation for each star (rather than $\langle V \rangle$) that can affect the distance determination by as much as ± 0.5 mag, we obtain a distance that is broadly consistent with that from the δ Cepheid and the features seen in the *HST* CMDs.

TABLE 4
WFPC2 PHOTOMETRY OF H94 CEPHEIDS

Variable	$B - V$	$V - I$	V	Period (days)	Notes
H94-V5	0.049	0.08	22.64	7	AC/W Vir?
H94-V9	0.559	0.31	22.23	2.7	δ Cepheid?
H94-V10	0.032	−0.012	22.52	13	AC/W Vir?

FIG. 8.—Spatial distribution in stellar density of differently selected stellar populations in Leo A as seen in the *HST* images of Leo A. The top panel shows the density distribution of the MS + BL (young, blue stars). The middle panel shows the RC stars distribution. The bottom panel shows the distribution of the RGB stars above the RC. The stellar density contours are labeled in the maps in units of number of stars per kiloparsec square area.

If we have found W Vir stars, this provides something of a dilemma, because they are typically very old stars usually seen in conjunction with BHBs. It is possible that at this very low metallicity the BLs are blue enough at a low luminosity to enter into this region of the instability strip as

FIG. 9.—Spatial density distribution of the red and blue stellar populations seen in the MDM images of Leo A. The top panel shows the density distribution of the MS + BL (young, blue stars). The bottom panel shows the distribution of the RGB stars. The stellar density contours are labeled in the maps in units of number of stars per square kiloparsec.

young stars. It is also possible that the BHB is hidden in the MS dominated by a young population. If we assume that these variables are in fact ACs, which makes the non-detection of a HB less of a problem, then it would follow that H94 misidentified the true periods of these variables. ACs typically have very short periods (< 3 days). As in Pegasus, these objects could also have much longer periods, of order hundreds of days. However, the blue colors do not match with the properties of the long-period variables found in other galaxies, which were extremely red (e.g., Tolstoy et al. 1995; Saha et al. 1996a). These variables in Leo A could also be eclipsing binaries misidentified by H94.

3.1.2. The Tip of the Red Giant Branch in Leo A

Determining the distance to a galaxy using the tip of the red giant branch (TRGB) is only reliable for galaxies with a predominantly old population (> 2 Gyr) and a moderate metallicity. For metallicities lower than 2% solar, assuming efficient convective overshooting, the upper mass limit for helium flash is only about $1.6\text{--}1.7 M_{\odot}$, and so the RGB phase transition only occurs after $1.3\text{--}1.5$ Gyr. The luminosity of the TRGB is thus a strong function of age in this

FIG. 10.—MDM Hiltner 2.5 m telescope calibrated CMD in I , $V-I$ used to check the calibration zero points of the *HST* data. The plot scale is the same as the *HST* CMD (Fig. 6), but the MDM CCD covers more area on the sky, and thus of Leo A than does *HST*. This means that the brighter, sparsely distributed populations are better represented in this CMD (e.g., the TRGB). [See the electronic edition of the *Journal* for a color version of this figure.]

regime (Sweigart, Greggio, & Renzini 1990), and so it cannot be reliably used as a distance indicator. The efficacy of the TRGB as a distance measure is also somewhat uncertain in star-forming, low-metallicity systems such as this, because the AGB population (if one exists) is distributed above the true TRGB without the characteristic downturn

FIG. 11.—MDM vs. *HST* photometric comparison for 15 stars that we found to be relatively isolated in the *HST* F814W chip 3 image. Chip 3 is the most crowded of the chips and was chosen because it gives us the largest sample of comparison stars. In the top plot we make the comparison for V , in the middle, I , in this bottom plot we show how the color of the stars appears to vary between the two calibrations. In the top two plots the cross in a square symbol represents the reddest stars in the sample that have $V-I > 0.8$. In the bottom plot this symbol represents the brighter stars in the sample where $I < 21$.

of higher metallicity AGB stars. Thus, depending upon the SFH of the galaxy, this could effectively mask the true tip.

The *HST* TRGB in Leo A is very indistinct due to the small number of stars populating it. The MDM field covers a much larger area, and hence we get a more accurate and clearer TRGB measurement of $m - M = 24.5 \pm 0.2$ (see Fig. 10) assuming that $M_I = -4$ from the calibration of Lee, Freedman, & Madore (1993) and that crowding is not a significant problem (e.g., Martinez-Delgado & Aparicio 1997). The presence of a clear TRGB in Figure 10 is an indicator that there is an old population in Leo A (older than 1–2 Gyr). As we show below (in § 4.3), however, the ratio of numbers of RC/RGB stars does not allow that this older population can be very large.

In Figure 12 we have overplotted observed RGB sequences of several Galactic globular clusters (from Da Costa & Armandroff 1990) for comparison with the observed Leo A RGB. This shows how varying the assumed distance effects the age and metallicity determination of the system with very little effect on the TRGB magnitude. All these values have to be consistent with what we know of Leo A. At $m - M = 24.6$ we either have to assume that the stars are not globular cluster age or that they are at an even lower metallicity than is M15, which, at $[\text{Fe}/\text{H}] = -2.2$, is one of the lowest metallicity globular clusters known. At $m - M = 24.2$ we can find stars that are consistent with an extremely metal-poor ($[\text{Fe}/\text{H}] = -1.9$) globular cluster age population in Leo A.

3.1.3. Leo A Red Clump

It has recently been shown that a well-defined RC can provide a useful distance determination (Cole 1998; Paczyński & Stanek 1998). RC stars are in the core helium-burning evolutionary phases, and their luminosity varies depending upon age, metallicity, and mass loss (e.g., Caputo, Castellani, & Degl'Innocenti 1995). The RC is relatively blue, and thus, consistent with the upper limits that can be assumed from the young population, we conclude that we see an extremely metal-poor RC ($Z \sim 0.0004$). We also note that this RC has a large extent in magnitude, ~ 1.1 mag in V . We can use this extent to estimate the age of the population that produced it using theoretical models (Caputo et al. 1995; Girardi, Bressan, & Bertelli 1998). This age measure is *independent of absolute magnitude and hence distance*.

The luminosity of the RC was computed from the I luminosity function between $0.65 < V - I < 0.95$ and $22 < I < 25$. The underlying RGB stars were removed using a linear fit to the wings of the I histogram and fitting the residuals (~ 2400 stars) to a Gaussian. Added weight was given to the peak I mag of the fitted Gaussian profile and the low-luminosity side of the histogram, because the high side is obviously contaminated by faint BL stars. Thus, the average RC is at $I = 23.77$, $V - I = 0.82$. Castellani & Degl'Innocenti (1995) computed isochrones for $Z = 0.0001$ and $Z = 0.0004$ for 0.7 to 20 Gyr populations and also made some RC models for the same metallicities (Caputo et al. 1995), and by using the total V extent of the RC, their models predict an upper limit to the age of the population assuming $M_I = -0.4$ for the RC. The Gaussian profile fitted to the I data has a width of 1.0 mag at 10% of the peak (or 1.1 mag in V). Assuming the youngest RC possible (1–2 Gyr) and a reddening, $A_I = 0.04$, the distance modulus, $m - M = 24.2 \pm 0.2$. If the RC is predominantly at its

FIG. 12.—We have overplotted RGB sequences from Da Costa & Armandroff 1990 for five globular clusters (M15, NGC 6397, NGC 6752, NGC 1851, and 47 Tuc) on our Leo A data. These clusters have, respectively, $[\text{Fe}/\text{H}] = (-2.17, -1.91, -1.54, -1.29, \text{ and } -0.71)$. They are plotted from right to left, with the lower metallicities the bluest. We have done this for two different distance moduli to show the uncertainty, as well as the implications of distance errors on the interpretation of these observations. [See the electronic edition of the *Journal* for a color version of this figure.]

oldest extreme (9–10 Gyr), then the distance of Leo A is 23.9 ± 0.1 , but this distance doesn't fit in with the BL or the TRGB.

Thus, the mean I mag by itself does not rule out an older RC, but the vertical extent does. This cannot be reproduced for ages older than a maximum of ~ 2.2 Gyr. A 1.5–2.2 Gyr old RC will have $M_I \sim -0.4 \pm 0.1$, which gives a distance of $M - m = 24.2 \pm 0.2$. For older (4.5–10 Gyr) and younger (0.8–1.5 Gyr) models, the RC is fainter, possibly as faint as $I = 0.0 \pm 0.1$, but these latter two possibilities are in conflict with the TRGB distance, for the old models; with the lack

of MS, for the young models; and with the BLs, in both cases. For an example of a RC clearly older than 2 Gyr, see the *Hipparcos* solar neighborhood CMD (Jimenez, Flynn, & Kotoneva 1998).

3.1.4. He-Burning Blue Loops in Leo A

Despite the uncertainty involved in BL physics we note that the Sextans A *HST* data shows excellent fits to the BL models (Dohm-Palmer et al. 1997b). We also note that the best-fitting distance to the BL models for Leo A appear able to match our data very well; at $Z = 0.0004$, they give $m - M = 24.1 \pm 0.1$. Because of the large uncertainties involved in creating theoretical models of BLs (e.g., Meynet 1992; Chiosi 1997) they are not generally very reliable distance indicators. There are several cases where the MS and the BL shapes are clearly inconsistent, e.g., in Pegasus (Gallagher et al. 1998).

3.1.5. New Distance to Leo A

Because we need to know an accurate distance to Leo A to interpret the CMD in terms of a SFH we chose the distance (from Table 3) that is consistent with the largest number of stars in the CMD, namely the stars in the RC, rather than the TRGB (a more typical distance measure, although there are strong caveats for galaxies like Leo A). The RC, as well as the luminosity (and shape) of the BLs, favors a distance modulus around 24.2. This distance is also broadly consistent with the low end of the variable star distance determinations and the TRGB. Thus, based on this new *HST* CMD, we assume the new distance to Leo A to be $m - M = 24.2 \pm 0.2$, where the error is purely the range that allows a reasonable fit to the CMD models.

3.2. Extinction Toward and Within Leo A

Burstein & Heiles (1984) give a low extinction of $E(B - V) = 0.02$ toward Leo A. Following the approach we used for the Pegasus dwarf (Gallagher et al. 1998), we checked the region for excess 100 μm far-infrared emission in the *IRAS* map; none was found that is consistent with the Burstein & Heiles estimate of the extinction. H I synthesis maps of Leo A by Young & Lo (1996) show peak internal column densities of less than $3 \times 10^{21} \text{ cm}^{-2}$. For an SMC extinction-to-gas ratio, the maximum internal extinction is predicted to be $E(B - V) < 0.03$ (Fitzpatrick 1985). Additional support for a low value of the extinction comes from the spectrophotometry of a planetary nebula in Leo A by Skillman et al. (1989). They found an anomalously low ratio of $\text{H}\alpha$ to $\text{H}\beta$ emission-line intensities in their data and thus see no evidence for extinction. We adopt as baseline values $A_B = 0.08$, $A_V = 0.06$, and $A_I = 0.02$ in our subsequent analysis of the Leo A CMDs.

There is circumstantial evidence from looking at the properties of background galaxies seen through Leo A that there may be variable internal extinction within the central regions of Leo A. Figure 13 shows a subsection of the WF3 chip containing two galaxies very close together that seemingly have quite different extinction properties. This of course may be due to some intrinsic difference in the properties of these galaxies—although typically background galaxies are to first order fairly similar (Tyson 1988; Lilly, Cowie, & Gardner 1991). So this is not conclusive proof (a more careful study is in progress; Tolstoy, Freudling, & Rosa 1998) but merely suggestive, and it fits in with other evidence for variable extinction seen in our CMDs. The scatter of stars between the MS and BL at $I \sim 22.5$ and

FIG. 13.—Three images through Leo A, which are taken from the WF3 chip. They are from top to bottom, in F814W, F555W, and F439W filters. Each image is 16" square (40 pc at distance of Leo A), and their limiting magnitudes are roughly similar ($I = 24.8$, $V = 25.8$, and $B = 25.3$).

further down the MS (to the red) may be the result of variable extinction through the star-forming regions in the center of Leo A. The distribution of these points is inconsistent with MSTOs for example. However, the global reddening toward Leo A seems to be correct because the MS lies where it should (unlike in Pegasus, Gallagher et al. 1998). Variable extinction may be common in irregular galaxies, and, for example, has been clearly identified in multi-color data in the area around SN 1987A in the LMC (Romaniello et al. 1998).

3.3. Current Metallicity of Leo A

The only metallicity determination for Leo A comes from a planetary nebula (PN) (Skillman et al. 1989), which happens to be the brightest $\text{H}\alpha$ source in the galaxy. The metallicity was found to be extraordinarily low, $12 + \log(\text{O}/\text{H}) = 7.3 \pm 0.2$ ($\sim 2.4\%$ solar), for a gas-rich star-forming galaxy.

The young population, specifically BLs, are the most sensitive global feature in a CMD to metallicity. They do not require an assumed age as the RGB does. The BLs in our

CMD are consistent with Padua (Fagotto et al. 1994) $Z = 0.0004$ (2% solar), and not with Geneva (Schaller et al. 1992) $Z = 0.001$ (5% solar) for any reasonable distance. This low value is also consistent with the Skillman et al. PN metallicity, but this galaxy is desperately in need of more detailed abundance work.

4. MAKING MODELS

It is important to understand the theoretical stellar evolution and atmosphere models being used and their limitations. Many different aspects of this are discussed in detail in Tolstoy (1996), Tolstoy & Saha (1996), and Gallagher et al. (1998). Errors in the models have very serious implications for Leo A because of the insensitivity of low-metallicity models to age variations on the RGB. The RGB isochrones crowd together in a very limited parameter space, and so small changes in stellar physics can change an optimum model from a young 2 Gyr old population to an old 10 Gyr population.

For all the modeling presented in this paper we have used either $Z = 0.001$ Geneva stellar evolution models (Schaller et al. 1992), or, most extensively, $Z = 0.0004$ Padua stellar evolution models (Fagotto et al. 1994). We do not like to “mix” models like this, and we note that when comparisons have been possible Geneva and Padua give different results for identical initial conditions and Padua tends to produce a redder RGB than does Geneva (see Fig. 11 in Gallagher et al. 1998). In all cases we have used the standard Kurucz (1991) models to convert the temperature and luminosities of the stellar evolution models into the observed colors in a CMD.

The Tolstoy (1996) distance and metallicity clearly don’t work for this new, more accurate data. It is relatively easy to mistake RGBs for RSG stars if the CMD is not sufficiently detailed to detect any other features (e.g., RC or HB). The poor match between new data and models isn’t merely a problem of distance but also metallicity. Changing the distance alone means that the RC is too faint and too red, and the RGB is also too red to ever match the observed data.

The other important considerations in the construction of CMD models are initial mass function (IMF) and incompleteness. We treat them in the same way as discussed in Tolstoy (1996) and Tolstoy & Saha (1996). Namely, we use a Salpeter IMF throughout. We are completely insensitive to any possible variations in the IMF because we are predominantly sampling stars with masses greater than $1 M_{\odot}$. In this *HST* data incompleteness due to crowding is not a problem (see Fig 2). This was checked on more crowded fields of Sextans A by Dohm-Palmer et al. (1997a). The incompleteness basically follows the photometric error distributions computed by DoPHOT. There is a much sharper cutoff at faint magnitudes than is typical for crowded fields.

We use the methods laid out in Tolstoy & Saha (1996) to compare our data with possible models and find the most likely model to match the observations. When we display our models we convolve the model with an error distribution to make it easier for the eye to see what is a good match to the data. This error distribution is taken straight from the measurement errors (shown in Fig. 7) and randomly added to each filter separately in the model. However, as explained in Tolstoy & Saha (1997), one of the strengths of this method of comparing data with models is that we compare them numerically using the measurement error that comes with every data point as a probability density to

predict the probability of a model being consistent with this measured point. In each case our favored model is one that maximizes the likelihood that the distribution of model points matches that of the data points within the observational errors on the data points. This of course assumes that a model is “perfect,” which for our purposes it is. It is not clear how to give theoretical models errors. However they were provided, we could easily incorporate them into our modeling code.

We split up our analysis of the CMD into two different areas, namely the “young” population (represented by the MS and BL stars, thus in the case of these observations back to ~ 1 Gyr ago) and the intermediate/old populations seen in the RC and RGB (~ 1 –10 Gyr). The approaches for these regimes are different, although we do not hold them entirely separate in the modeling process, because the contribution of the young BL stars overlying the older RC is important.

4.1. Metallicity Evolution

Accounting for metallicity evolution in a CMD model is difficult. It is impossible to determine a unique model based solely on the RGB. This is because the variation of stellar evolutionary tracks with metal levels and distributions is not necessarily linear; as a result, simple interpolations between tracks with widely spaced metallicities can be misleading. However, if metallicity evolution is neglected in a CMD model, then the best model for that galaxy will be younger than if metallicity evolution were included.

When a galaxy makes stars, then the detritus of this process (e.g., from S/N explosions and stellar winds) make it unlikely that the galaxy can avoid metallicity evolution all together (e.g., Eggen, Lynden-Bell, & Sandage 1962). However, there is no concrete observational evidence that this is true, although abundance ratios of different elements do give us model-dependent suggestions (e.g., Pagel 1994). In the disk of our Galaxy, for example, it was recently shown that although there is a general trend in metallicity evolution with time, the scatter is always large (Edvardsson et al. 1993). We do not understand in detail how stars interact with their surrounding ISM and thus how current star formation feeds the metal enrichment of future generations. Looking at recent results of absorption-line studies of Zinc abundances at cosmological distances ($z = 0.7$ –3.4) there is again evidence for a shallow evolution of metallicity in galaxies over this long redshift range, but there is also a large scatter in values at any time (Pettini et al. 1997). Absorption-line studies of these species provides arguably the most reliable estimator of the metallicity of the *gas* in a galaxy. If suitable background continuum sources could be found behind nearby galaxies this would dramatically improve our understanding of how the ISM in different galaxies evolves and is affected by the proximity of current star formation.

However, in the absence of these probes we are forced to rely upon the emission-line measure of H II regions and PNs. While the reliability of these measurements has been questioned because of concerns of “pollution” of these regions by the products of massive star evolution (Kunth & Sargent 1986), recent studies have found no evidence for this effect (e.g., Kobulnicky & Skillman 1997 and references therein). In addition to providing measurements of the present ISM metallicity, these emission-line studies can provide hints about the past chemical enrichment of the

surrounding ISM (e.g., Skillman, Bomans, & Kobulnicky 1997). Models can be made from emission-line ratios (e.g., C/O and N/O) that indicate a possible global secular chemical enrichment history for a galaxy (e.g., Kobulnicky & Skillman 1998) if it can be assumed that H II regions are representative of the global environment, as discussed at length in Kobulnicky & Skillman (1998).

At the low metallicity of Leo A, the age-metallicity degeneracy is particularly acute (Da Costa 1997) and so only sensitive to gross changes in assumptions. Another practical problem with fitting any kind of metallicity evolution in Leo A is that for the young population we are already using the lowest metallicity set of consistent model stellar evolution tracks available and so there is no parameter space left to model more metal-poor stars. There is even some argument about what is the lowest metallicity that an object can have and with Leo A we are pretty close to perceived limits for galaxies (Kunth & Sargent 1986).

Even though it would be desirable to include metallicity evolution, it is not clear how to do this. If we interpolate between different metallicity tracks we are going through very uncertain parameter space. Metallicity is not a parameter in a star that can be so easily described. The only way to be able to do this properly is to have a much finer grid of models at different metallicities. This is not yet available. Thus we opt not to include the effects of metallicity evolution in our modeling, but to mention how a further decrease in the metallicity going back in time would alter our conclusions.

4.2. The “Young” Population: The Main Sequence and the He-Burning Blue Loop Stars

We know that Leo A is currently forming stars. It has several faint H II regions, and we see a distinct MS and BL stars in the CMDs (see Fig. 6). Comparing our observed CMDs with theoretical stellar evolution models we can determine the recent SFH of this galaxy.

First of all we determine the evolutionary timescales to which we are most sensitive. The MS luminosity distribution means that we can detect MSTOs between 800 Myr old (we are restricted from going further back in age by the sensitivity limits of our data) and ~ 10 Myr, which is our saturation limit and means that stars younger than this are too bright for our detector. Although we are sensitive to star formation at all times along the MS, we are not able to characterize it well because we cannot detect the most massive turnoff stars. Toward the base of the MS we become less and less sensitive to anything but large variations in the SFR. This is partly due to increasing error and incompleteness uncertainties, but also due to the fact that any variations in SFR further back in time are “hidden” by subsequent star formation going on until the present overlying the entire MS.

The BL color and luminosity are able to give us detailed SFR information back to just beyond 1 Gyr ago. The BLs are more luminous than the stars of the same age on the MS and hence the BL is valuable in giving us accurate information to feed into MS models. Subsequent epochs of star formation do not overlie each other on the BLs (unlike on the MS). However, after about 900 Myr the BL and the RC stars merge together at this metallicity, and it is difficult to accurately disentangle them. Unfortunately, in the current data, the MS is not deep enough to help disentangle the BL/RC confusion uniquely.

Another feature of a very young population are the RSGs which have a vertical sequence extending above and slightly blueward of the RGB. These are very young stars corresponding to roughly the ages and masses of the BL stars at the same luminosity.

Our detailed modeling of the young population along the MS and BLs of Leo A within the above limits results in the following conclusions:

1. The gap in the BL sequence ($I \sim 23$, $V - I \sim 0.4$), combined with the relative numbers on the upper and lower main-sequence, point to a gap in star formation between 500–900 Myr ago. The 500 and 900 Myr limits come from the blue and red extents of the gap.

2. The spread of stars at the bottom of the CMD is inconsistent purely with error scatter, although it is very easy to underestimate the errors and the incompleteness of data close to the observational limits especially in WFPC2 data with the warm pixel problems (cf. Dohm-Palmer et al. 1997a). An active period of star formation about 900 Myr ago (consistent with the BL gap) would have MSTOs populating this area of the diagram (see Fig. 14). We are limited by the implications such a turnoff has for the number of stars predicted higher up in the RC/RGB. But it is likely that some stars from lower (older) MSTOs to which we are not directly sensitive are more likely to be up scattered and thus produce a higher number of stars at the younger turnoff at the edge of our observational limits.

3. The relative numbers of stars on the MS and BLs are consistent with a more or less constant SFR over the last 500 Myr. There are variations in the stellar number densities, which suggest that this has not been completely smooth, although there is no evidence for more than a factor around 2 variation over this time period (see Fig. 15).

4.3. The “Intermediate” Age Population: The Red Clump and the Red Giant Branch

The dominant population of red stars in Leo A resides in an RC [$N(\text{RC}) \sim 2400$ stars in I , $V - I$], which has already been discussed in § 3.1.3. There is also a relatively weak RGB [$N(\text{RGB}) \sim 570$ stars in I , $V - I$] extending above the RC. The ratio of the numbers of stars in these two phases [$N(\text{RC})/N(\text{RGB})$] is very sensitive to the SFH of the galaxy. The classical RC and RGB appear in a population at about the same time (~ 0.9 – 1.5 Gyr, depending on model details), where the RGB are the progenitors of the RC stars. The feature that ties these phases together is the explosive ignition of helium under degenerate conditions at the RGB tip (the helium flash). There is a RC, therefore there was a helium flash. This results in a near-constant M_{core} for RC stars between $1.7 < M_{\text{star}} < 0.8 M_{\odot}$ and hence near-constant RC lifetime, t_{RC} . The age of onset of the helium flash is between 0.9 and 1.5 Gyr. Regardless of the absolute timescale the ratio of $N(\text{RC})/N(\text{RGB})$ in Leo A is a firm indication that the galaxy is right around the age of helium flash onset. But this isn’t a very precise indicator because the RGB lifetimes depend on stellar mass and because of mass loss there is no unique mapping from RGB to RC mass. Massive RGB stars build core mass more quickly than their low-mass counterparts and thus achieve helium ignition in a short amount of time; t_{RGB} is a strongly decreasing function of M_{star} . Hence the ratio, $t_{\text{RC}}/t_{\text{RGB}}$, is a decreasing function of the age of the dominant stellar popu-

FIG. 14.—(a) Optimum model for the young stellar population (<1.5 Gyr old), $Z = 0.0004$ metallicity, and assuming constant star formation overplotted on the data. (b) Our optimum model for the young stellar population (<1.5 Gyr old), $Z = 0.0004$ metallicity, and assuming a burst of star formation ended 900 Myr ago and began at least 1.5 Gyr ago, and another epoch of star formation began 500 Myr ago and continues to the present. The data is in black. The main difference between these two plots is seen at the faint end of the CMD, where the burst model produces more stars along the faint limit of the observations. The difference is very slight to the eye, but it significantly improves various aspects of the model/data comparison, which highlights the importance of numerical comparisons between models and data.

lation in a galaxy. Thus, the higher the ratio, $N(\text{RC})/N(\text{RGB})$, the younger the dominant stellar population in a galaxy. For Leo A the $N(\text{RC})/N(\text{RGB}) = 4.4$, which suggests that the RC is very young. A predominantly much older model contains either no RC (>9 Gyr) or an under luminous one (2–9 Gyr), as shown in Figure 16, where this ratio tends to ~ 1 . In Pegasus we see a slightly older (and

FIG. 15.—SFR vs. time derived using the Dohm-Palmer method from the luminosity function for stars identified as being on the core-HeB phase. The bins are 100 Myr wide. The data have been dereddened and corrected for incompleteness. The assumed IMF has a Salpeter slope. Error bars refer only to statistical uncertainties due to the number of stars in each bin.

more metal-rich) RC, where $N(\text{RC})/N(\text{RGB}) \sim 2$ (Gallagher et al. 1998), which suggests a RC age of 4–5 Gyr.

For a given metallicity the RGB red and blue limits are given by the young and old limits of the stars populating it. For $Z = 0.0004$ the youngest stars to populate the RGB (rather than the supergiant regions) are ~ 1 Gyr. As a stellar population ages the RGB moves to the red, for constant metallicity, the red edge is determined by the age of the oldest stars. If there is metallicity evolution, then the age-metallicity degeneracy makes it impossible to disentangle these two effects on the basis of the optical colors of the RGB.

The RGB below the RC also gives some limits to the older MSTO ages. Although these limits are fairly similar to those on the MS, they provide a useful consistency test for assumptions made about a burst of star formation ending 0.9 Gyr ago.

Our detailed modeling of the RC in Leo A leads to the following conclusions:

1. The optimum model for the number of stars in the RC relative to the RGB and the luminosity distribution of the clump itself, is one in which the RC formed in a short “burst” of star formation over the period 900–1500 Myr ago. This fits in with the young stellar population models based on the MS and BLs. If the RC models are accurate it is not possible to match significantly older RC to the data. The RGB however matches only much older models (9–10 Gyr).

2. A young model does have problems, the most serious of which is that any successful RC model makes the young RGB around 0.2 mag too blue in $V-I$ at the TRGB and a decreasing offset down to zero at the RC. This could be due to a problem with the stellar physics used in the models. It is well known that the red extent of the RGB is very sensitive to the assumed core mass on the RGB and hence to assumptions made about the evolution of the core. Given that the Padua RGB is typically redder than the Geneva RGB for the same mass star at higher metallicities (e.g., Gallagher et al. 1998), it might be that Geneva tracks, using

FIG. 16.—(a) Optimum model of the RC ($\sim 1\text{--}2$ Gyr old) superposed upon the data (black points). (b) Our optimum model of the RGB ($\sim 9\text{--}10$ Gyr) in superposed upon the data (black points). Clearly these models cannot be made consistent with each other.

slightly different assumptions about stellar physics (e.g., different values of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ cross section) would give a more consistent picture between RC and RGB ages.

3. There is a possible AGB star population, as would be expected for a predominantly $0.9\text{--}1.5$ Gyr old population, directly above the TRGB. The Padua isochrones predict that AGB stars would lie directly above the TRGB at this metallicity, with no turnover to the red (Bertelli et al. 1994). Some of the bright stars significantly redward of the RGB may also be evolved AGB or carbon stars. Spectroscopy or infrared imaging would confirm this.

In summary, comparing our data with Padua 2% of solar metallicity theoretical stellar evolution model tracks suggests that the RC is very young and the RGB is very old. It is not clear that we can reconcile these two results with the

numbers of RC and RGB stars in the data. We prefer the young RC model that fits most of the data and results in a predominantly young galaxy. Based on the young RC model at least 60% of the stars ever formed in this galaxy were formed in a short burst of star formation about 900–1500 Myr ago. In determining the length and intensity of this burst, we have to trade off the number of stars at different luminosities in the RC. If we did not have a problem with the inferred color of the RGB we could assume that the entire galaxy was less than a few gigayears old.

4.4. Is There a Globular Cluster Age “Old” Population?

The fact that the optimum RC model does not properly predict the observed RGB data may either suggest that the theoretical models are in error or that there is an underlying much older population in Leo A. Exactly how much older is impossible to determine without deeper photometry and information about the metallicity evolution within Leo A. The only indications of an old population in the present data are buried in the RGB and in the HB branch region. In star-forming systems the HB is quite easy to “lose” in the MS and MSTOs. The RGB similarly is overlaid by the number of different age populations and is impossible to disentangle because of the age-metallicity degeneracy.

Our exploration of the existence of a much older population in Leo A results in the following conclusions:

1. If the theoretical models and the *HST* calibration is to be believed, then the observed RGB fits the 2% Padua models for a 9–10 Gyr old population. This old a population does not have a RC, although it does assume that a HB is hidden in the “noise” of the MSTOs in this star-forming galaxy. It is difficult to obtain even a limit for the presence (or lack) of a HB with the current data. But, relying on the RC and HB for an indication of an old or intermediate-age population is risky. These relatively short-lived phases of evolution can show dramatic variations in their CMD morphology between SFH scenarios with bursts of star formation rather than uniform SFR over a long period of time

2. To avoid relying only on theoretical models we also compared our data with observed globular cluster RGBs (Da Costa & Armandroff 1990) in Figure 12. The globular cluster RGB that best matches the Leo A RGB is NGC 6397, which is consistent with a much older (> 10 Gyr) and more metal-poor ($[\text{Fe}/\text{H}] = -1.9$, 1.2% solar) population. If we do not wish to include significant metallicity evolution, and indeed, a more metal-poor galaxy than 2% has never been observed in emission, then the observed RGB is too blue for the matching metallicity RGB ($[\text{Fe}/\text{H}] = -1.7$). Hence Leo A could be considerably younger than a globular cluster.

3. We cannot expect a large old population because the RGB is so sparsely populated. The modeling of the MS + BL + RC can account for at least 90% of the stars seen in the present CMD, so any globular cluster age population can represent only 10% of the star formation in Leo A.

To summarize, the theoretical models suggest we have an old population, at least 9–10 Gyr old. This is a very uncertain number because of the small number of stars we detect in the RGB, the absence of a clear HB, and our total lack of information about the metallicity evolution with time in this galaxy. It is also possible that either the stellar evolu-

tion models or the stellar atmosphere models converting temperature and luminosity to observed colors are inaccurate in this low-metallicity, young regime and that the RGB is solely young. This would be most consistent with the RC modeling. Another, more worrying possibility is that there is an error in the standard calibration of the *HST* filters. Thus, we can neither rule out the presence of an old stellar component in Leo A nor unequivocally prove there has to be one.

4.5. An Optimally Matched Model for the Leo A CMD

The modeling presented in the above three sections results in the combined optimum model shown in Figure 17. There are two panels on this plot. One shows the model in red and the other splits up the different age components

that make up the model (less than 500 Myr, 900–1500 Myr, and 9–10 Gyr) into three different colors. This last plot shows up the different age stellar populations and where they contribute. The following points are clear from Figure 17:

1. This model matches the observed MS effectively. The small scatter to the red side is presumed to be due to non-uniform reddening intrinsic to Leo A or to the presence of binary stars.
2. The RC is modeled convincingly, although no possible model for the RC can match the RGB distribution. This maybe be due to failings in the theoretical models used or to the *HST* calibration.
3. There are data not matched by the RC model that could not be helped by any extra BL or RC model (or

FIG. 17.—Our overall optimum model, where the SFH that this presumes is shown in Fig. 18. The top plot shows the complete model; in the bottom panel, the different age star formation epochs that contributed to this distribution are separated out. The young population (0–500 Myr), the intermediate-age “burst” of star formation (900–1500 Myr), and the possible underlying old population (9–10 Gyr), are shown.

mixture thereof). This is probably due to underestimates of the errors or incompleteness at fainter red magnitudes and perhaps also the effects of variable reddening and/or binary stars. There could also be HB stars here, or faint BL stars, which some models (e.g., Girardi et al. 1998) predict to lie 0.1–0.3 mag below the RC.

4. The RGB can be well matched only by the Padua models of very old ages.

Thus, we are confident that we have managed to match the major features in the CMD with these models. It is by no means a unique model, and the mismatch of the observed and model RGB is a cause of serious problems in finding the optimum model using the Tolstoy & Saha (1996) methods. The MS and BL make it obvious that there has been fairly active SFR over the last 500 Myr, and the RC makes it hard to avoid a fairly strong peak in the SFR 0.9–1.5 Gyr ago. The exact duration and intensity of these star formation periods are dependent on small number statistics. If there were significant metallicity evolution the conclusions based on the RC would alter. If the RC were more metal-poor (e.g., $Z = 0.0001$) than the MS then its maximum age would be older than that based on $Z = 0.0004$ models, but only by a few hundred million years (Castellani & Degl’Innocenti 1995). In our optimum model in Figure 17 we also include an old population. This population appears to fit the RGB stellar distribution very well, but it is strongly reliant on the stellar evolution and atmosphere models, which are not well tested in this regime. This conclusion also assumes that our *HST* data has been accurately calibrated (see comparison with ground based data in § 2.1 and Fig. 9).

5. A PROPOSED STAR FORMATION HISTORY OF LEO A

In Figure 18 we show the proposed SFH for Leo A that created the optimum CMD model in Figure 17. We use pseudo units to describe our SFR because we have not calibrated these values onto an absolute scale. The SFH in Figure 18 is split into two parts with differing time

FIG. 18.—One possible self-consistent SFH for Leo A that matches most of the data very well. We have not been able to estimate the effects of metallicity evolution because we lack a consistent set of models at metallicities lower than those used for our youngest stars. As described in the text the errors are not statistical, they merely give an indication of how flexible the SFR at any time can be before significantly affecting the good match of this model to the data.

resolution. The error bars give a rough estimate of the reliability of a given SFR. During the quiescent periods it gives an estimate of the intensity of SFR that would be difficult to hide. This is a difficult error to make absolute. We can hide a starburst of less than 5 pseudo-SFR units of short duration ($< 10^8$ yr) between 2 and 10 Gyr quite easily. But if there are too many of them, or one lasts too long then there will be problems for the model (the RGB will become overpopulated and perhaps structured). The error bars make no allowance for errors in distance, reddening, metallicity, or model inaccuracies. These are the major error sources of uncertainty in creating this SFH. If one of them is wrong the whole scenario presented here could change dramatically. The error bars in Figure 18 are not directly related solely to the statistics of the number of stars involved. It is very hard to simply put error bars down in the strictest meaning of an error bar. If there is any variation in the number of stars in one “element” of the SFH this will affect other elements to maintain a good match to the data.

The younger regime in the top panel of Figure 18 is that to which we are most sensitive to small variations in the SFR with time. We have MS information over the last 800 Myr that gives the most accurate SFR measure versus time, although with decreasing accuracy with time from the present because of increasing errors and smaller number of stars from the older populations. The SFR over the MS is broadly consistent with a constant SFR over the last 500 Myr. Between 500 and 900 Myr the data are consistent with either zero or a much lower SFR in Leo A. This comes from the gap in the BLs clearly seen just blueward of the RC. This may be a statistical effect in the sampling of the BLs, but it also ties in with our number density along the MS.

In the intermediate-age range the RC gives us limits to the SFR that must have created it, but it is very insensitive to any variations in the SFR during this period. Thus we know the RC contains stars older than 900 Myr but younger than 1500 Myr from its luminosity range and the ratio $N(\text{RC})/N(\text{RGB})$ stars, but we cannot be sure if the SFR was constant or varying between these limits.

In the bottom panel we show the old population seen in Figure 17. This is highly speculative more than 2 Gyr in the past. The long gap with apparently zero star formation represents the gap in the models between the young RGB (at 0.9–1.5 Gyr) and the old one (at 9–10 Gyr). This gap could be made to disappear if it were found that the young RGB models were too blue or in the case of a calibration error. Presuming this quiescent era in the galaxy is real, it is possible that there were short bursts of star formation all through this period rather than the prolonged period at 10 Gyr. However this would require a steady metal enrichment during this period to keep the RGB so narrow. We also must conserve the total number of stars found on the RGB so the amount of star formation possible greater than 2 Gyr ago has a hard limit from the number of stars seen on the RGB.

One place that we can gain some insights into possible age-metallicity correlations in very small galaxies is from the Galactic dSph systems. While all of these objects currently contain neither cool gas nor young stars, they clearly were small, star-forming galaxies only a few gigayears ago (see Smecker-Hane et al. 1994; Stetson, Hesser, & Smecker-Hane 1998). Like most dwarf galaxies, mass and mean stellar metallicity roughly correlate with galaxy mass in

dSph systems (see Gallagher & Wyse 1994; Mateo 1998), but it is not clear that metallicity relates to stellar *ages*, particularly in the Carina dSph. The dSph therefore serve as warning that age-metallicity relationships are not necessarily simple, even in extreme dwarf galaxies and it is therefore premature to assume that we know the form of the age-metallicity relationship, if one exists at all, in Leo A.

We note that, consistent with our CMD modeling, the unusual fraction of true/anomalous Cepheids hints that this galaxy must have had a higher SFR in the past than at present, and/or that the metallicity affects this ratio. If we assume that the faint variables are young AC or W Vir stars this suggests that the SFR in this galaxy was higher at some point around 1–3 Gyr from the present. The exact magnitude of past SFRs is difficult to predict from these observations alone because of the small-number statistics and the incompleteness errors in monitoring these galaxies from the ground. This is broadly consistent with our model based on the CMD properties.

On the basis of these new *HST* observations, H94 primarily detected some kind of W Vir or AC type of object, which are known to closely resemble their brighter cousins, but to be ~ 2 – 2.5 mag fainter. These are thought to be “young” single star W Vir/AC stars due to the fact that the Leo A CMD does not contain any obvious indications of a population older than the 1–2 Gyr old RC, although the models for the RGB suggest that there could be a globular cluster age old metal-poor population. There is no obvious HB, especially no obvious BHB. However, as is seen in Leo I (Mateo et al. 1994; Gallart et al. 1998), a lack of an HB is necessary but not sufficient proof that there is no old stellar component. The Leo I *HST* data shows distinct old MSTOs, but no corresponding HB.

6. CONCLUSIONS

Our data indicate that the majority of stars in the Leo A dwarf irregular galaxy have ages of less than a few gigayears. Is this reasonable? One way to test this conclusion is to see if other galaxies show independent evidence for star formation in the comparatively recent past. For example, if our model is correct, then we might expect to see a considerable range in mean stellar population ages among other extreme dwarf galaxies in the Local Group. Since Leo A is currently dim ($M_V = -11.4$ for our adopted distance; see Mateo 1998), we should be comparing it with the smallest dwarfs, which are mainly dSph systems.

The stellar populations of Local Group dSph galaxies are being explored in detail through a combination of ground-

based and space-based observations (see reviews by Gallagher & Wyse 1994; Da Costa 1994, 1997; Mateo 1998). These investigations reveal that several of the Galactic dSph contain large complements of intermediate-age stars, e.g., Carina (Smecker-Hane et al. 1994) and Leo I (Lee, Freedman, & Madore 1993; Caputo et al. 1996), while other dSph, such as the Ursa Minor system, are mainly composed of ancient, globular cluster age stellar populations. Leo I has an especially prominent intermediate-age stellar population component that was probably formed a few gigayears ago. The dSph therefore display the kind of range in stellar ages that one might expect if major star-forming episodes have occurred sporadically in small galaxies during the past 10 Gyr or so. That we are seeing Leo A at a time when most of the stars have formed in the past few gigayears is evidently not a special case but instead seems to be a relatively common phenomenon.

There remains a distinct possibility that Leo A is a purely young system. The ambiguities in interpreting the RGB mean that we still need to find unequivocal proof of an old population (e.g., RR Lyr variable stars or old MSTOs). The new closer distance for Leo A makes it possible to observe stars as faint as $M_V = +4$, equivalent to globular cluster age MSTOs. Stellar spectroscopy is also possible of RGB stars to try and look for evidence of metallicity evolution. In any case, Leo A is an excellent candidate for further study of star formation in a very low-metallicity environment. Even if it does not contain solely a young population, it is still the nearest by example of what an FBG may look like.

Support for this work was provided by NASA through grant GO-5915 from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 3-26555. Partial support from a NASA LTSARP grant NAG W-3189 is gratefully acknowledged. We thank the referee for very useful comments that improved our presentation. R. D.-P. would like to thank the graduate school of the University of Minnesota for a dissertation fellowship. J. S. G. expresses his appreciation for partial travel support from ST-ECF and ESO that made visits to Garching possible. E. T. thanks Ralph Bohlin for research support in the early phases of this project, and Michael Rosa, Chris Burrows, Carme Gallart, Alfred Gautschy, Fred Lo, and Cesare Chiosi for useful discussions. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

APPENDIX

VARIABLE STARS

The instability strip, where stars become unstable and thus pulsate and vary in brightness, appears to go through the entire Hertzsprung-Russell diagram (see Fig. 1 in Gautschy & Saio 1995), and the basic properties are, in principle, well-understood (e.g., Gautschy & Saio 1995, 1996, and references therein). The instability strip for the classical Cepheids (δ Cepheids) continues down in mass to include RR Lyrae, BL Herculis, W Virginis, RV Tauri, and even Mira variable stars (e.g., in 47 Tuc). The bluer and hotter anomalous cepheids (ACs) are also in this instability strip at higher mass.

The δ Cepheids are 3 – $15 M_\odot$ stars whose evolutionary tracks take them through the HRD instability strip. They vary uniformly and reliably obey a tight well-calibrated PL relation, which allows them to be one of the most important *primary* distance indicators (e.g., Sandage & Tammann 1968). At the very low-mass end are the RR Lyrae variable stars, which also have a well calibrated PL relation used for accurate distance determinations. They are typically HB stars. In between RR

Lyrae and δ Cepheids is a rather poorly studied “gap” (see Fig. 6 in Hoffmeister, Richter, & Wenzel 1982), through which the instability strip passes. Here lie the BL Her and AC variables.

The literature contains very few studies of these “nonclassical” (e.g., W Vir, AC) variable stars (e.g., Nemec, Nemec, & Lutz 1994), certainly not in the studies of stellar populations outside our Galaxy halo or the Magellanic Clouds. Early definitions of how to detect them is “they will be 2.5 mag fainter than the classical Cepheids” (Baade & Swope 1963), and in general most prescriptions for identifying them continue to rest upon previous detections of δ Cephei or RR Lyr variables, or some inherent knowledge of the properties of the region being searched (e.g., Wallerstein & Cox 1984). These nonclassical Cepheids have often been called “Population II Cepheids” (to distinguish from δ Cepheids, or “Population I Cepheids”), but this has long been known to be frequently an inaccurate wording (e.g., Woolley 1966; Richter 1967).

W Vir and RV Tau variable stars are thought to be post-HB stars that pass through the instability strip on their way to the AGB as they exhaust the helium in their cores (Gautschy & Saio 1996; Sandage, Diethelm, & Tammann 1994). Since the evolutionary timescale of the core helium exhaustion phase is much faster than the core helium burning phase, the number of these stars is typically much smaller than the RR Lyr stars. However this ratio might change in the case of a short burst of star formation. It is also completely unknown if it is possible that young helium burning BL stars could cross into these same unstable region of parameter space at very low metallicities. Young, extremely metal-poor stars exist in a very understudied region of parameter space. W Vir stars are typically bluer than δ Cepheids (Fernie 1964; Dickens & Carey 1967; Eggen 1961) and even have their own PL relation (Eggen 1961):

$$M_V = -0.13 - 1.90 \log P.$$

This relation has a different slope from those of classical Cepheids, and this means they can be between 1 and 2.5 mag brighter than their classical cousins, depending upon their pulsation period.

ACs have shorter periods, are more massive than W Vir stars, and are known to have two possible separate evolutionary paths, neither of which comes from a post-HB phase (e.g., Bono et al. 1997; Smith & Stryker 1986). They can be either single stars, thus much younger than the RR Lyr population, at 1–4 Gyr old, or they can be binary stars where mass transfer has taken place. In this last case, for example, a binary of two stars of $0.9 M_\odot$ can be as old as ~ 10 Gyr (Renzini, Sweigart, & Mengel 1977). They have their own PL relation, with a metallicity dependence (Nemec et al. 1994) which is for the fundamental pulsation mode

$$M_V = -0.10 - 3.13(\pm 0.28) \log P + 0.32[\text{Fe}/\text{H}].$$

The SMC is known to contain a number of ACs (Graham 1975), whereas none (or few) have been detected in the LMC (e.g., Graham 1975, 1977, 1985). As the LMC and SMC are thought to have similar, not to say inextricably linked, SFHs, this has been suggested to be a metallicity effect (Smith & Stryker 1986). Thus, one might expect an unusually large number of ACs in Leo A, which is an extremely metal-poor galaxy. Thus, we cannot take the identification of “Population II” Cepheids as conclusive proof of globular cluster age stars because there are typically old and young evolutionary paths to these variable stars.

Classifying variable stars is a very complex and difficult especially with only a single filter, but since we can show that these variables in Leo A follow the W Vir PL relation, and if this can proven to be the case (with better sampling of the light curves), then we leave it as a problem for the theorists to explain why we observe that stars of these masses entering the instability strip.

The uncertainties in the different populations of variable stars that we have found call into question the efficacy of using small numbers of Cepheid variable stars in either small galaxies with a peculiar SFH, and/or in galaxies with extremely low metallicity ($\sim 2\%$ solar) without a lot of care and attention to properly sampling light curves in more than one color. This conclusion also highlights the dangers of not considering the consequences of “peculiar” SFHs on the stellar population of a galaxy as a whole. If it is assumed that a galaxy has been forming stars continuously for a number of gigayears when in fact there have been several short epochs of star formation then several properties and their implications maybe be misjudged. Distance indicators, such as Cepheid variable stars, have been designed and proven for large galaxies that typically have had fairly constant SFR over the past few gigayears. If they are applied in other circumstances without due care and attention, then problems may occur.

REFERENCES

- Aparicio, A. 1994, *ApJ*, 437, 27
 Baade, W., & Swope, H. H. 1963, *AJ*, 68, 435
 Babul, A., & Ferguson, H. C. 1996, *ApJ*, 458, 100
 Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., & Nasi, E. 1994, *A&AS*, 106, 275
 Biretta, J. A., et al. 1996, *WFPC2 Instrument Handbook* (version 4; Baltimore, STScI)
 Bono, G., Caputo, F., Santolamazza, P., Cassisi, S., & Piersimoni, A. 1997, *AJ*, 113, 2209
 Burstein, D., & Heiles, C. 1984, *ApJS*, 54, 33
 Caputo, F., Castellani, V., & Degl’Innocenti, S. 1995, *A&A*, 304, 365
 ———, 1996, *A&A*, 309, 413
 Castellani, V., & Degl’Innocenti, S. 1995, *A&A*, 298, 827
 Chiosi, C. 1997, in *Stellar Astrophysics for the Local Group*, ed. A. Aparicio, A. Herrero, & F. Sanchez (Cambridge: Cambridge Univ. Press), in press
 Cole, A. A. 1998, *ApJ*, 500, L137
 Da Costa, G. S. 1994, in *Proc. Third CTIO/ESO Workshop on the Local Group*, ed. A. Layden, R. C. Smith, & J. Storm (Garching: ESO), 101
 ———, 1997, in *Stellar Astrophysics for the Local Groups*, ed. A. Aparicio, A. Herrero, & F. Sanchez (Cambridge: Cambridge Univ. Press), in press
 Da Costa, G. S., & Armandroff, T. E. 1990, *AJ*, 100, 162
 Dekel, A., & Silk, J. 1996, *ApJ*, 303, 39
 Dickens, R. J., & Carey, J. V. 1967, *R. Obs. Bull. Greenwich*, No. 129, E340
 Dohm-Palmer, R. C., Skillman, E. D., Saha, A., Tolstoy, E., Gallagher, J. S., Hoessel, J. G., Mateo, M., & Chiosi, C. 1997a, *AJ*, 114, 2527
 ———, 1997b, *AJ*, 114, 2514
 Dohm-Palmer, R. C., Skillman, E. D., Saha, A., Tolstoy, E., Mateo, M., Gallagher, J. S., Hoessel, J. G., Chiosi, C., & Dufour, R. J. 1998, *AJ*, submitted
 Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D. L., Nissen, P. E., & Tomkin, J. 1993, *A&A*, 275, 101
 Eggen, O. J. 1961, *R. Obs. Bull.*, No. 29
 Eggen, O. J., Lynden-Bell, D., & Sandage, A. R. 1962, *ApJ*, 136, 748

- Ellis, R. 1997, *ARA&A*, 35, 389
- Fagotto, F., Bressan, A., Bertelli, G., & Chiosi, C. 1994, *A&AS*, 104, 365
- Fernie, J. D. 1964, *AJ*, 69, 258
- Fitzpatrick, E. L. 1985, *ApJS*, 59, 77
- Fruchter, A., & Hook, R. 1996, in *The Hubble Space Telescope and the High Redshift Universe*, ed. N. R. Tanvir & A. Aragón-Salamanca (Singapore: World Sci.), 137
- Gallagher, J. S., Tolstoy, E., Dohm-Palmer, R. C., Skillman, E. D., Cole, A. A., Hoessel, J. G., Saha, A., & Mateo, M. 1998, *AJ*, 115, 1869
- Gallagher, J. S., & Wyse, R. F. G. 1994, *PASP*, 106, 1225
- Gautschi, A., & Saio, H. 1995, *ARA&A*, 33, 75
- . 1996, *ARA&A*, 34, 551
- Girardi, M., Bressan, A., & Bertelli, G. 1998, in preparation
- Glazebrook, K., Ellis, R., Colless, M., Broadhurst, T., Allington-Smith, J., & Tanvir, N. 1995, *MNRAS*, 273, 157
- Graham, J. A. 1975, *PASP*, 87, 641
- . 1977, *PASP*, 89, 425
- . 1985, *PASP*, 97, 676
- Hensler, G., & Burkert, A. 1990, *Ap&SS*, 170, 231
- Hoessel, J. G., Saha, A., Krist, J., & Danielson, G. E. 1994, *AJ*, 108, 645 (H94)
- Hoffmeister, C., Richter, G., & Wenzel, W. 1982, *Veränderliche Sterne*, 28
- Holtzman, J. A., Burrows, C. J., Casertano, S., Hester, J., Trauger, J. T., Watson, A. M., & Worthey, G. 1995, *PASP*, 107, 1065
- Hunsburger, S. D., Charlton, J. C., & Zaritsky, D. 1996, *ApJ*, 462, 50
- Hunter, D. A., Hawley, W. N., & Gallagher, J. S. 1993, *AJ*, 106, 1797
- Jimenez, R., Flynn, C., & Kotoneva, E. 1998, *MNRAS*, in press (astro-ph/9709056)
- Kepner, J. V., Babul, A., & Spergel, D. N. 1997, *ApJ*, 487, 61
- Kobulnicky, H. A., & Skillman, E. D. 1997, *ApJ*, 489, 636
- . 1998, *ApJ*, 497, 601
- Kunth, D., & Sargent, W. L. W. 1986, *ApJ*, 300, 496
- Kurucz, R. L. 1991, in *Stellar Atmospheres: Beyond Classical Models*, ed. R. Haynes & D. Milne (NATO ASI Ser. C, Vol. 341) (Dordrecht: Kluwer), 279
- Lee, M. G., Freedman, W. L., & Madore, B. F. 1993, *ApJ*, 417, 553
- Lee, M. G., Freedman, W. L., Mateo, M., Thompson, I., Roth, M., & Ruiz, M.-T. 1993, *AJ*, 106, 1420
- Lilly, S. J., Cowie, L. L., & Gardner, J. P. 1991, *ApJ*, 369, 79
- Lilly, S. J., Le Fevre, O., Hammer, F., & Crampton, D. 1996, *ApJ*, 460, 1
- Martinez-Delgado, D., & Aparicio, A. 1997, *ApJ*, 480, 107
- Mateo, M. 1998, *ARA&A*, in press
- Mateo, M., Olszewski, E. W., Lee, M.-G., Saha, A., Hodge, P., Keane, M., Suntzeff, N., Freedman, W., & Thompson, I. 1994, *BAAS*, 185, 51.03
- Matteucci, F., & Tosi, M. 1985, *MNRAS*, 217, 391
- Meynet, G. 1992, in *The Feedback of Chemical Evolution on the Stellar Content of Galaxies*, ed. D. Alloin & G. Stasinska (Meudon: Obs. Paris), 40
- Nemec, J. M., Nemec, A. F. L., & Lutz, T. E. 1994, *AJ*, 108, 222
- Odewahn, S. C., Windhorst, R. A., Driver, S. P., & Keel, W. C. 1996, *ApJ*, 472, 13
- Paczynski, B., & Stanek, K. Z. 1998, *ApJ*, 494, L219
- Pagel, B. E. J. 1994, in *The Formation and Evolution of Galaxies*, ed. C. Muñoz-Tuñón & F. Sánchez (Cambridge: Cambridge Univ. Press), 149
- Pettini, M., Smith, L. J., King, D. L., & Hunstead, R. W. 1997, *ApJ*, 486, 665
- Renzini, A., Sweigert, A., & Mengel, J. 1977, *A&A*, 56, 369
- Richter, G. 1967, *Veröff. Sternw. Sonneburg*, 7, 3
- Romaniello, M. 1998, in *The Magellanic Clouds and Other Dwarf Galaxies*, ed. T. Richtler & J. M. Braum (Aachen: Shaker), in press
- Saha, A., Hoessel, J. G., Krist, J., & Danielson, G. E. 1996a, *AJ*, 111, 197
- Saha, A., Sandage, A., Labdardt, L., Tammann, G. A., Macchetto, F. D., & Panagia, N. 1996b, *ApJ*, 466, 65
- Sandage, A., Diethelm, R., & Tammann, G. A. 1994, *A&A*, 283, 111
- Sandage, A. R., & Tammann, G. A. 1968, *ApJ*, 151, 531
- Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, *A&AS*, 96, 269
- Schechter, P., Mateo, M., & Saha, A. 1993, *PASP*, 105, 1342
- Silk, J., Wyse, R. F. G., & Shields, G. A. 1987, *ApJ*, 322, L59
- Skillman, E. D. 1998, *The Magellanic Clouds and other Dwarf Galaxies*, ed. T. Richtler & J. M. Braum (Aachen: Shaker), in press
- Skillman, E. D., Bomans, D. J., & Kobulnicky, H. A. 1997, *ApJ*, 474, 205
- Skillman, E. D., Kennicutt, R. C., & Hodge, P. 1989, *ApJ*, 347, 875
- Smecker-Hane, T. A., Stetson, P. B., Hesser, J. E., & Lehnert, M. D. 1994, *AJ*, 108, 507
- Smith, H. A., & Stryker, L. L. 1986, *AJ*, 92, 328
- Spaans, M., & Norman, C. 1997, *ApJ*, 483, 87
- Stetson, P. B., Hesser, J. E., & Smecker-Hane, T. A. 1998, *PASP*, 110, 533
- Sweigert, A. V., Greggio, L., & Renzini, A. 1990, *ApJ*, 364, 527
- Tolstoy, E. 1996, *ApJ*, 462, 684
- . 1998, in *Dwarf Galaxies and Cosmology*, ed. T. X. Thuan, C. Balkowski, V. Cayatte, & J. Tran Thanh, in press
- Tolstoy, E., Freudling, W., & Rosa, M. 1998, in preparation
- Tolstoy, E., Saha, A., Hoessel, J. G., & Danielson, G. E. 1995, *AJ*, 109, 579
- Tolstoy, E., & Saha, A. 1996, *ApJ*, 462, 672
- Tyson, J. A. 1988, *AJ*, 96, 1
- van den Bergh, S. 1994, in *Proc. Third CTIO/ESO Workshop on the Local Group*, ed. A. Layden, R. C. Smith, & J. Storm (Garching: ESO), 3
- Wallerstein, G., & Cox, A. N. 1984, *PASP*, 96, 677
- Woolley, R. 1966, *Observatory*, 86, 76
- Young, L. M., & Lo, K. Y. 1996, *ApJ*, 462, 203