Scientific Justification

Context: A fundamental prediction of galaxy formation models is the mass function of galaxies, which we observe via the luminosity function (LF). The shape of the faint end of the LF is a powerful discriminator between models, but has been difficult to constrain observationally. The Local Group remains the only environment with a reliable census of dwarfs down to $M_V \simeq -10$ and in this case the number of low-mass dwarfs falls significantly below the number of low-mass halos predicted by numerical simulations (Klypin et al. 1999, Moore et al. 1999). While UV ionizing flux in the early Universe could account for fewer of these halos yielding luminous dwarfs (*c.f.* Bullock et al. 2000), determination of the full LF (to the faintest dwarfs) in additional groups and other environments are very important to understanding the processes of luminous galaxy formation and evolution.

Recent observations are starting to converge on the parameterization of the *bright* end of the LF (see Driver & de Propis 2003 for a review); however, the distribution of dwarf galaxies fainter than $M > -16$ has been little surveyed beyond our local volume. Due to their low luminosity and low surface brightness, dwarfs are notoriously difficult to observe. Beyond the Local Group, photometric surveys have attempted to push down to dwarf luminosities in nearby groups and clusters, and showed a general trend of larger relative fractions of dwarf galaxies in denser environments (*c.f.* Trentham & Tully 2002). This result, however, depends strongly upon the robustness of the membership determination at the faint end, which has largely depended upon indirect methods. At distances typically beyond 15 Mpc, LF studies to date have relied on morphological classification and statistical background subtraction at the faint end. To date, these techniques have a mixed record of success. For example, morphological classification has successfully identified dwarf members of Virgo (Drinkwater et al. 1996), but in the Coma cluster, spectroscopic follow-up of faint dwarf galaxy candidates has identified an unexpectedly large fraction of background galaxies (Adami et al. 2000). The only truly reliable way to determine membership is to measure a distance for each galaxy.

Our Program: We have a large program to measure the LFs in the nearby Leo I and Coma I groups (Flint et al. 2001). Leo I is a low-density Local Group analogue although it has some interesting differences – it contains a large elliptical (NGC 3379) and a huge HI ring at its core. The Coma I Cloud is a much larger group which spans a large dynamic range of densities. Both are at a distance of 10 Mpc, giving us the opportunity to uniquely determine membership for each galaxy through redshifts or direct distance measurement. Our ultimate goals are to measure the LF to intrinsically faint levels for comparison with the Local Group LF and identifying a new sample of dwarf spheroidal galaxies at 10 Mpc to be used for further characterization of the population of dwarf galaxies.

Our Leo I survey nears completion. Candidates were identified using a match-filtering technique on deep, R-band MOSAIC images of over seven square degrees. Initial candidate selection relied upon morphological membership classification, and we have continued to refine our group membership via follow-up observations. The current state of the Leo I sample is shown in the luminosity function in Figure 1. The the filled histogram shows the confirmed members to date, and the open histogram shows all remaining galaxy candidates, statistically corrected for completeness and membership probability (fully described in Flint et al. 2004).Fitting the statistical luminosity function with the standard Schechter function yields a faint-end slope roughly consistent with that of the Local Group LF, $\alpha = -1.2$. We are now attempting to confirm membership for each of these candidates individually.

Our follow-up observational program over the past three years has utilized Keck's LRIS and ESI, the Lick 3m and the MOS on WIYN to obtain follow-up spectroscopy, the KPNO 2.1m for multi-band colors of the candidates, ESI at Keck to measure surface-brightness fluctuations (SBF) in candidates, and Arecibo for HI observations of all candidates. We find that Leo I members and candidates are unusually gas-poor, with almost all HI detections resulting from confusion with the central gas ring and so yielding little information about membership. For the dwarf spheroidal candidates, we find that our ground-based SBF measurements suffer from difficulties with profile removal and few pixels within which to reliably measure fluctuations due to their low surface brightnesses and small sizes, which has complicated direct distance determinations. As we conclude our follow-up program, to date we have identified a number of initial candidates as background (as expected), but also have verified membership for galaxies as faint as $M_R \sim -11$.

Despite our efforts, some of the most compelling candidate galaxies remain unconfirmed. These galaxies are amongst the lowest luminosity and the lowest surface brightnesses of our candidates (shown as the open symbols in Figure 2). To definitely determine the faint-end slope of the LF down to our completeness limits of $\mu_R(0) \simeq 24.5$, $M_R \simeq -11$, we require complete membership information for these lowest luminosity galaxies. Yet, these are also the most challenging candidates for direct membership evaluation.

This Proposal: The best candidate low-luminosity dwarfs are large ($> 15''$ in diameter) with very low surface brightness and smooth (no internal structure) exponential profiles. These are either dSph galaxies in Leo or distant, low-surface brightness 'lurking giants' of the type discovered by Dalcanton et al. (1997). Under the best conditions at Keck (FWHM 0.35 arcsec) we can just barely resolve the brightest giant-branch stars at the distance of Leo. We have in fact done so for two cases, but clearly we cannot count on having these conditions from the ground. We have five remaining low-luminosity Leo candidates which, based on photometric and structural properties, are very likely dwarfs in Leo. We propose to image these with the WFC on ACS to resolve the stars at the tip of the red-giant and determine the distances to these galaxies.

A classic method for measuring distances follows Baade (1944) when he resolved the brightest red giant branch stars in M32 and NGC 205, and established them as companions to M31 by comparing their magnitudes with M31 giant stars. Using the luminosity of the tip of the red giant branch (TRGB) as a standard candle has evolved into a robust distance indicator. Globular cluster observations and models indicate that the TRGB has $M_I = -4.0$, and that it is constant across a wide range of metallicities, $-2.2 < [\mathrm{Fe/H}] < -0.7$ dex, and ages, 7 to 17 Gyr (*c.f.* Lee, Freedman, & Madore 1993). If our candidate dwarfs are at the mean distance to the Leo I group, 10 Mpc, the TRGB would have $m_I \sim 26$. This has been demonstrated by Sakai et al. (1997) for the Leo I giant elliptical, NGC 3379, with a measured TRGB of $m_I = 26.30$.

We propose to do an experiment very similar in spirit to Baade (1944), where we will attempt to resolve the stars in our dwarf candidates and compare their magnitudes to those found in NGC 3379, which is independent of the absolute calibration of the TRGB distance method. We intend to image six candidate LSB dwarfs using the F814W filter (roughly equivalent to I band), and to extend approximately one magnitude fainter than the expected TRGB magnitude to $m_I = 27.4$. This will then probe galaxy distances up to the Leo I distance of 10 Mpc, and approximately 2 Mpc beyond. According to simulations by Madore & Freedman (1995), this should yield a distance accurate to ~ 10%. However, the simple criterion of whether or not the galaxy resolves into stars will tell us immediately if these candidates are dwarfs at the distance of the Leo Group or background objects (likely intrinsically large low-SB galaxies).

Targets: Of our most likely dwarf candidates, we have six remaining without membership confirmation. Listed in Table 1, each have $\mu_R(0) > 22.5$, and are larger than $15''$ in diameter at $\mu_R =$ 26mag/$''^2$. Four of these galaxies had no detectable HI down to a mass limit of $M_{HI} > 10^6 M_\odot$ (assuming they are in Leo), suggesting they are gas-poor dwarf spheroidals. The remaining two had robust HI detections at the velocity of the group, but both were close enough to the central HI ring that there may be a confusion problem. If the distance of these two galaxies is confirmed, they would fall amongst the lowest-M_{HI} dwarfs known.

A last interesting aspect of these galaxies is three of the six appear to have unresolved nuclei (there is arguably one nucleated dwarf in the Local Group). This is a very interesting possible population difference between the Leo Group and Local Group. The high resolution of the ACS images would also allow us to resolve the nuclei in these two galaxies, confirming them as nucleated dwarfs. Measuring the properties of the nuclei, such as tidal radius, would allow comparison with models wherein nuclei are related to very massive globular clusters (*c.f.* Oh & Lin 2000).

Why HST?: The extreme low-surface brightness nature of these dwarf galaxies has made follow-up observations from the ground exceedingly difficult. We have additional Keck time in the Spring of 2003 to complete spectroscopic follow-up of the higher-surface brightness candidates in the Leo Group, but these five objects require the proposed ACS observations to establish membership. These objects have $\mu_R(0) > 22.5$, which requires several hours of integration per object even with a 10-m class telescope for a $S/N \sim 10$ spectrum. In addition, a background group along the line of sight to the group at $v = 1288$ km s^{-1} overlaps in velocity space with Leo I ($v = 820$ km s^{-1}), but lies anywhere from 1.5 – 2 times farther in distance. Measuring the TRGB with ACS easily determines the distance of these elusive objects to 10%, and easily distinguishes group members from the background group.

References:

Adami, C., Ulmer, M. P., Durret, F., Nichol, R. C., Mazure, A., Holden, B. P., Romer, A. K., & Savine, C. 2000, A&A, 353, 930

Baade, W., 1944, ApJ, 100, 137

Bullock, J. S., Kravtsov, A. V., & Weinberg, D. H. 2000

Dalcanton, J., Spergel, D.N., Gunn, J.E., Smith, M., & Schneider, D.P. 1997, AJ, 114, 635

Drinkwater, M. J. , Currie, M. J., Young, C. K., Hardy, E., & Yearsley, J. M. 1996, MNRAS, 279, 595

Driver, S. & De Propris, R. 2003, Ap&SS, 285, 175

Flint, K., Metevier, A. J., Bolte, M. & Mendes de Oliveira, C. 2001, ApJS, 134, 53.

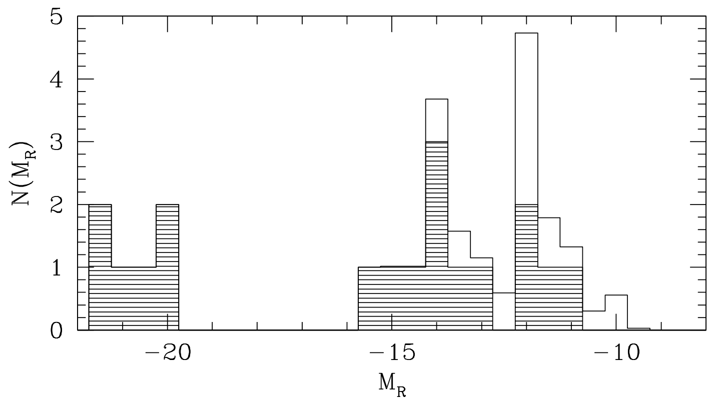

Figure 1: Leo I luminosity function: filled histogram indicates confirmed members, and the open histogram shows the total remaining candidate sample, statistically corrected for membership and completeness.

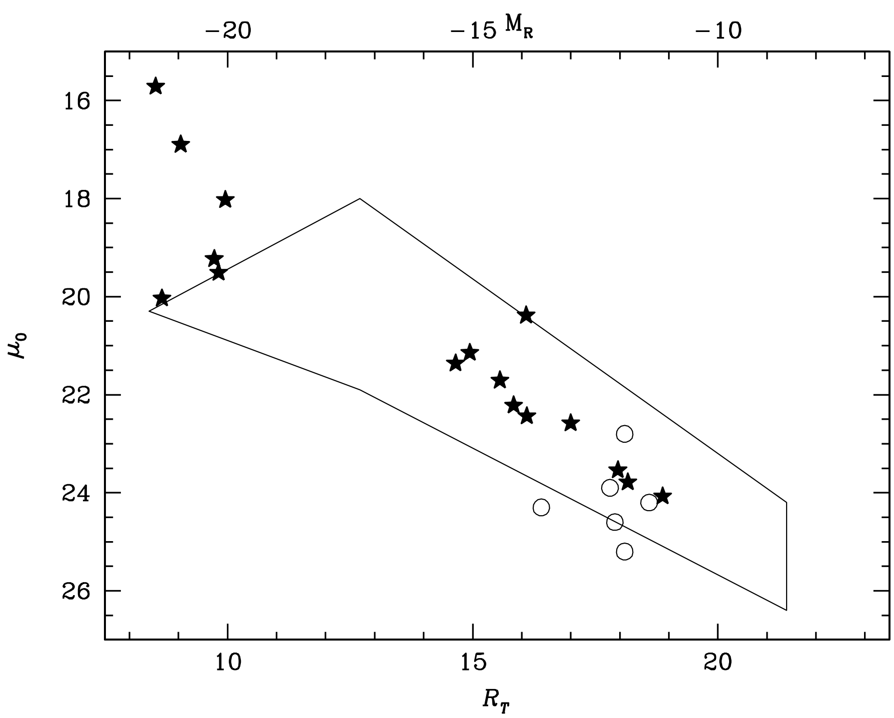

Figure 2: Leo I confirmed members (stars) and targets of this proposal (circles), plotting total apparent R-band magnitude vs. central, R-band surface brightness. Boxed area shows parameter space occupied by Local Group galaxies at this distance, 10 Mpc.

Name	RA(2000)	Dec(2000)	R	$\mu_R(0)$	v(km/s)	M_{HI}
LEO104813+115811[2]	10:48:12.8	11:58:10.9	18.1	22.8	944[1]	1.77e+07
LEO15[2]	10:46:30.2	11:45:19.0	17.8	23.9	–	–
LEO21	10:46:57.6	12:59:49.8	18.6	24.2	841[1]	6.53e+06
KK96	10:50:26.9	12:21:32.0	16.4	24.3	–	–
F1L-4[2]	10:49:25.8	12:33:08.6	17.9	24.6	–	–
F4L-5	10:47:13.3	12:48:04.0	18.1	25.2	–	–

Table 1: Targets

[1]HI velocity, possibly confused
[3]Possibly nucleated

Flint, K., Bolte, M. & Mendes de Oliveira, C. 2004, in preparation

Klypin, A., Kravtsov, A.V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82

Lee, M.G., Freedman, W.L., & Madore, B.F., 1993, ApJ, 417, 553

Madore, B.F. & Freedman, W.L., 1995, AJ, 109, 1645

Moore, B., Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J., & Tozzi, P. 1999, ApJ, 524, L19

Oh, K. S., & Lin, D. N. C. 2000, ApJ, 543, 620

Sakai, S., Madore, B.F., Freedman, W.L., Lauer, T.R., Ajhar, E.A., & Baum, W.A., 1997, ApJ, 478, 49

Trentham, N. & Tully, R. B. 2002, MNRAS, 335, 712

Description of the Observations

We propose to obtain deep I (F814W) images of six LSB dwarf candidates using the wide-field channel (WFC) of the Advanced Camera for Surveys (ACS). This will allow a direct comparison to the TRGB observations already available in the Leo Group (Sakai et al., 1997) and also minimize the required exposure times to resolve these red stars. Exposure times were chosen to provide SNR$=10$ at $m_{\rm I}=27.4$ which is one magnitude fainter than the TRGB magnitude for Leo Group members. The total open-shutter time required per galaxy is 243 minutes. With 52 minutes of visibility per orbit, including overheads for roughly two <20 minutes exposures per orbit using the standard dither pattern with 2.5 arcsec steps to remove the chip-gap region, these observations fit efficiently into 5 orbits per galaxy for a total of 30 orbits for the program.

As discussed above, one simple test for membership will be whether or not we resolve the galaxies into stars with these images. For Leo Group members we will be able to go one step further and use the TRGB method to measure distances to $\sim 10\%$.

■ Special Requirements

None.

■ Coordinated Observations

None.

■ Justify Duplications

None.

■ Previous Related HST Programs

None.