Deep UV Imaging of Galaxies in the Fornax Cluster

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ABSTRACT

We compare the Astro-1 Ultraviolet Imaging Telescope (UIT) deep image of the Fornax cluster with deep optical surveys for purposes of determining the efficacy of vaccuum ultraviolet imaging in terms of the recovery of very faint and/or diffuse galaxies. This field covers approximately 1/3 of a square degree and contains 15 galaxies with B_t brighter than 18.0 magnitude. A 1000 second near UV image detected 10 of these galaxies. These 10 detections include 3 luminous ellipticals, 2 bonafide dwarf ellipticals and 5 galaxies of small angular size that may or may not be members of the Fornax cluster. IF these optically faint galaxies are members of the Fornax cluster, then the VUV imaging did sample an appreciable range in the galaxy luminosity function. For the dwarf ellipticals, a comparison of their optical and UV fluxes indicates the UV light is not dominated by any hot population but rather represents the general UV characteristics of the underlying stellar population. In particular, we can place an upper limit of 25 O3-5 stars that are present due to possible low level star formation. Furthermore, the UV-optical colors of the dEs are significantly redder than Galactic globular clusters which indicates that these dEs do not have a significant population of extreme horizontal branch stars. With the failure of the near UV camera aboard the Astro-2 mission, the opportuntity for performing a deeper near UV survey has been lost. We conclude, however, that such a survey would have good sensitivity to the detection of optically faint and/or diffuse galaxies and would provide credible information on the galaxy luminosity function.

Subject headings: galaxies: Ultraviolet Observations;

1. Introduction

The detection of galaxies involves imaging of intrinsically diffuse objects against a noisy background. The kinds of galaxies which can be detected depends critically on the amplitude of the sky background and the characteristic noise of the detector. After approximately 100 years of constructing galaxy catalogs from imaging observations performed in the optical band, it is now clear that standard catalogs of galaxies are relatively biased in that they do not adequately represent galaxies which have low optical surface brightness. Confirmation of this is provided by the last decade of observation. As galaxy surveys push further below the level of the night sky brightness, large numbers of low surface brightness (LSB) galaxies are being discovered (*e. g.* Bothun et al 1991, Schombert et al 1992, Impey et al 1996). Recent analysis of this data by McGaugh et al (1995) suggests that 50% of the total population of rotating disk galaxies has central surface brightnesses fainter than 22.0 mag arcsec^{-2} . The percentage population of LSB dwarfs is substantially larger than this. Hence, there is considerable astrophysical interest in detecting intrinsically diffuse galaxies as they may contain a substantial fraction of the total baryonic material in the Universe.

In general, the secure detection of very diffuse galaxies requires a linear detector with good flat-fielding characteristics in combination with a very low background. Ironically, the current population of known LSBs has all been discovered using poor detector technology - namely photographic plates. The simple fact that large numbers of these objects were discovered this way implies that with better imaging technology yet more diffuse galaxies should become apparent. One potential technique is to image the sky in passbands in which the ambient background sky brightness is at a minimum. As first documented by O'Connell (1987) the sky background in the vaccumm ultraviolet (VUV $\sim$2500 Å) is very

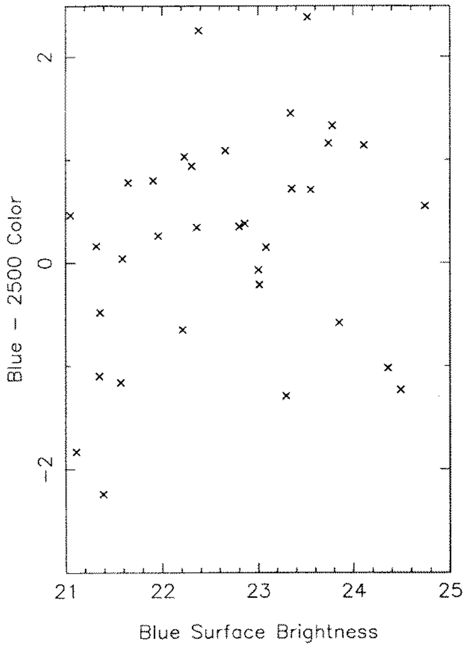

Fig. 1.— UV-B color plotted against mean blue surface brightness for a sample of face-on spiral galaxies observed with the ANS satellite. All measurements are made through a 2.5x2.5 square arcminute aperature. The data have not been corrected for foreground or internal reddening. Positive values indicate UV bright galaxies.

low. His original estimate of this sky brightness was VUV_{sky} ~27.0 mag arcsec^{-2} . This low background in principle is conducive for the detection of optically faint and/or diffuse galaxies that would not be easily detected at longer wavelengths. To date, this expectation has not been empirically tested to any great extent. In this chapter, we compare deep UV images of the Fornax cluster with the deep optical survey of Fornax, using Malinized plates, of Bothun et al (1991) to determine if UV imaging is a promising technique for detecting optically faint and/or LSB galaxies.

2. Potential Sensitivity of UV Imaging

The Ultraviolet Imaging Telescope (UIT- see Stecher et al 1992) recorded an ambient sky brightness of VUV_{sky} ~25.0 mag arcsec^{-2} . This is approximately 2 mag arcsec^{-2} brighter than the original estimate of O'Connell (1987). This increase in sky brightness is due to a number of effects but appears to be dominated by scattered moonlight and the low orbit of the shuttle picking up airglow (Waller et al 1996). Although these are UV magnitudes (see Stecher et al 1992) the magnitude scale does allow for a favorable comparison with the more familiar optical magnitude system. Comparing the B-UV color of the sky to stellar populations in galaxies allows for an initial estimation of the detectability of galaxies in the VUV as a function of surface brightness.

In standard magnitude units the B-UV color of sky is ~-2.5 – -2.0 which we now compare to the colors of real galaxies. Figure 1 shows the available data for spirals of all types. The UV data come from ANS satellite observations which utilized a square 2.5x2.5 ′aperture centered on the galaxy. The galaxies in the ANS sample were selected to be face-on so as to minimize the potentially large effects of internal reddening on emitted UV flux. Most of these galaxies have distances less than 15 Mpc. To get the B-UV color, B-band CCD images were obtained using the MDM 1.3-m telescope and the mean blue surface brightness was measured through the equivalent square 2.5x2.5 ′ANS aperture. In general, the galaxies in this sample have diameters that greatly exceed this aperture size. For most of these large spiral galaxies, this aperture contains 5–30% of the total B-band luminosity and hence we are really measuring a central mean blue surface brightness. We are thus using this relation between (local) blue surface brightness and UV-blue color only as being indicative of the global blue surface brightness – UV-color relation.

There is a rather large dispersion in the 2500-blue (herafter 25-B) Å color and little correlation with central mean blue surface brightness. The data exhibit a range of ~5 magnitudes in B-UV color over a range of ~3 magnitudes in mean blue surface brightness.

To first order this indicates that mean blue surface brightness brightness is an unreliable indicator of UV surface brightness which is our main point in presenting this data. Although none of the galaxies in the ANS sample are LSB galaxies in the global sense, there are a handful which have a mean blue surface brightness fainter than 23.5 mag arcsec^{-2} through the 2.5x2.5 $'$ANS aperture. This local surface brightness is comparable to the global mean for the LSB samples of Schombert et al 1992 and Impey et al 1996. The tendency for some galaxies to have locally low optical SB but normal local UV surface brightness further illustrates the decoupling of these two passbands and suggests that galaxies with *globally* low optical SB might be detectable in 2500 Å passband imaging observations.

For actively star-forming spirals, O and B stars dominate the 2500 Å surface brightnesses. This surface brightness is 2–3 mag arcsec^{-2} brighter than the blue. The associated A and F stars with this population has less of a contribution to increasing the mean surface brightness in the blue. For pure Population II systems, such as the bulge of M81 or NGC 2841, the surface brightness at 2500 Å is down, relative to the blue, by 2 mag arcsec^{-2} . It is, of course, difficult to estimate *a priori* what the total 25-B color will be for LSB galaxies but it is likely bracketed between the pure Pop II and the OB star dominated cases. Furthermore, although the UBV colors of LSB disks are as blue or bluer than Sc I's, we shouldn't assume a similar 25-B color due to the obvious lack of current star formation.

If we consider a mean 25-B color of 0.0 for these objects, then a LSB galaxy with B(0) = 25.0 mag arcsec^{-2} would have VUV(0) = 25.0 mag arcsec^{-2} , which instead of being $\sim$10% of sky, is now equal to the sky value. In the unlikely case where the B-UV color of LSB disks is as red as it is for spiral bulges, then those objects with B(0) = 25.0 mag arcsec^{-2} would have an equivalent 2500 Å surface brightness of 27.0; 17% of the sky background at this wavelength. This signal is detectable even if the ability to flat-field is only good to

2–3%. Thus, the dark background of the VUV is most definitely conducive for the discovery of diffuse galaxies.

We had hoped to fully exploit this during the Astro-2 Space Shuttle mission by taking the longest possible nighttime exposures (∼2000 seconds) through the broad-band A1 filter. The planned 6 deep exposures during the 15 day mission would result in ∼2 square degrees of sky coverage making this the deepest and widest UV survey yet performed. To calibrate the sensitivity of these observations to the detection of optically diffuse galaxies, each field center contained a previously discovered LSB galaxy. Unfortunately, there was a *complete* failure in the first stage image intensifier of the A camera during the Astro-2 mission. No astronomical images were recorded on the A camera film during the entire mission and hence this opportunity was lost. As UIT is unlikely to fly again, the chance for doing this kind of deep UV survey work with existing space instruments appears irretrievably lost. Hence, to compare real data with the expectation that VUV observations are good for finding very faint and/or diffuse galaxies we have no recourse but to re-analyze the deepest Astro-1 images. However, this data set is severely limited as very few of these images have exposure times that exceed 500s. In the course of reviewing the data quality of the Astro-1 images we were able to identify one exposure that went sufficiently deep, and which contained known diffuse galaxies.

Here we report on the galaxy identification and UV-optical colors for the deepest Astro I field that was obtained. This field is centered on NGC 1399 in the Fornax cluster and has a total exposure time of ∼1000 seconds. Although numerous studies have been done on the UV properties of both NGC 1399 and NGC 1404 (i.e. Burstein et. al. 1988, Ferguson et. al. 1991) this was the first long ultraviolet exposure of the surrounding galaxies. This same field has been deeply surveyed for LSB galaxies by both Caldwell and Bothun (1987) and Bothun et al (1991). With the deep optical surveys at our disposal, we were able to dig

Table 2: Galaxies with B_{mag} $\leq$18.0 not found in FUV or NUV fields.

Galaxy	B_{mag}	Type
FCC 222	15.3	dE0,N
FCC 211	16.3	dE0,N
FCCB 1263	17.2	interact.
FCCB 1241	17.3	dE3, pec?
FCC 208	17.3	dE2,N
FCCB 1321	17.7	S

deeply into the noise of the Astro I image to recover those galaxies that were barely detected. These UIT images have resulted in the UV detection of ten galaxies located within a radius of 20' from NGC 1399. We report on the fluxes and colors of these galaxies, some of which are optically faint, and make a determination of the efficacy at which vacuum UV imaging can detect faint galaxies.

3. Observations and Data Reduction

Two images were taken of the 20' radius region centered on RA 3:36:35, Dec -35:32:24. The first image was taken through a broad-band near ultraviolet (NUV) fused SiO_2 filter. The NUV filter's peak is 2763 Å, with a bandwidth of 1147 Å. The second image was taken through UIT's far ultraviolet (FUV) broadband filter, a SrF_2 filter with peak wavelength of 1443 Åand bandwidth 354 Å. The NUV and FUV images had 1097 and 1457 second exposure times, respectively. The original data is on Kodak IIa0 70mm film. The photographs were digitized by scanning with a Perkin-Elmer model microdensitometer, producing a 16 bit 2048 by 2048 image. The images were then corrected for background

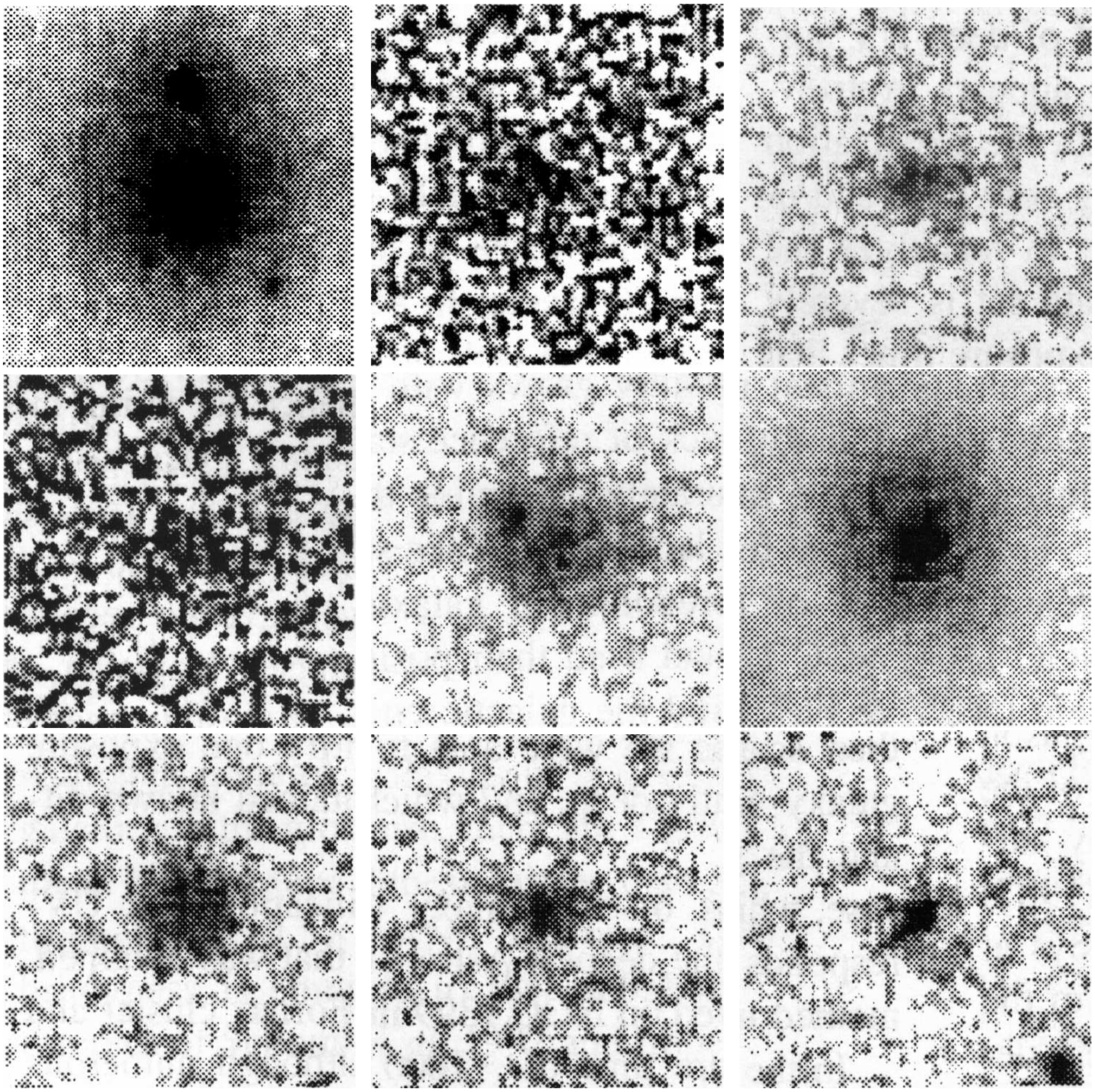

Fig. 2.— Greyscale representation of the nine detected NUV galaxies. From top left, the galaxies are: NGC 1399, FCCB 1396, FCCB 1237, FCC 207, FCCB 1374, NGC 1404, FCCB 1364, FCCB 1353, Galaxy X.

fog, linearized, and flat-fielded. Details of the image reduction technique, as well as of the UIT, are given in Stecher, et. al. (1992).

Our procedure for detecting and identifying galaxies consisted of two steps. In the first step, we found all connected pixels which exceeded the threshold criterion of 3σ above the local background. We called these detections and then sought a positional match between the RNGC catalog and/or the catalogs of Caldwell (1987), Caldwell and Bothun (1987), Ferguson (1989) and Bothun et al 1991). In the second step, we used optical positions to determine if there was marginally significant flux in the UV images at the optical position. As discussed below, the NUV image is much deeper than the FUV image so all detections were made on the NUV image; that is, we did not require a detection in both UV passbands to consider the object as being a real galaxy. The second step, discussed in more detail below, suffered from relatively poor astrometry in the UV image. In particular, the field center position, while roughly centered on NGC 1399, is not known within an accuracy of better than 10 arcseconds. In addition, the field rotation is arbitrary and without the lack of reference SAO stars, it is rather difficult to accurately de-rotate the field to the cardinal directions. As a result, positional uncertainty grows with radius from the field center. Finally, the lack of reference stars also makes it almost impossible to accurately determine the pixel scale.

To compensate for the lack of reference stars , we initially identified three of the predominant galaxies (NGC1399, NGC1404, NGC1396) and used their position within each field (NUV & FUV) to find the galactic coordinates of that field's center and to define the de-rotation axis. Each field was then scanned by eye for other galaxies. Once a candidate galaxy was found, its galactic coordinates were determined and the galaxy was identified from published lists. In one case, which we denote as Galaxy X, the NUV detection corresponds to what appears to be a faint galaxy that has remained uncataloged.

In the second step, a search was made at the positions of all 27 known galaxies which should lie within the field and were not found on our first pass. ¿From the objects detected in the first pass, we estimate that the relative astrometry between optical catalogs and the NUV image has an r.m.s. error of $20''$. Using the optical positions for aperture placement, we found no significant intensity change (an area ≥ 2 pixels^2 with intensity $> 1\ \sigma$ above the local background) at these positions, and thus no additional galaxies were detected using this procedure. We are thus fairly confident that we have correctly identified all the galaxies that were detected in the NUV frame.

We estimated the limiting magnitude in the NUV and FUV frames by adding images of artificial galaxies with known magnitudes and positions, and then applying a consistent search algorithm to detect them and measure their brightness (see also Smith et al 1996). This procedure shows that the FUV image has a limiting magnitude of $m_{lim}(1500) =\sim 18.5$ and for the NUV image $m_{lim}(2500) =\sim 19.0$.

Figure 2 shows a grey scale representation of the 10 detections in the NUV field. Not surprisingly, most of the detected galaxies have rather low signal-to-noise. Had not a previously deep optical survey been available, its doubtful whether these detections would be considered real, though they are all more than $3\ \sigma$ above the local background. In all cases, insepction of the optically deep images revealed a faint and/or diffuse galaxy co-inciding with the UV detection. Due to the low signal to noise ratio in the images, the IRAF centroiding routines failed to converge. Hence the center was found by eye. Photometric errors were was determined by shifting the center slightly and comparing the results. Using this estimate for the center, aperture photometry was performed using QPHOT. Local sky was determined by measurements in an annulus around the object. Fairly large apertures were used in determining the total UV magnitude as the PSF for the Astro-1 images is rather large. Fortunately, unlike the optical Universe, there are very few foreground stars present on these images to contaminate the aperture measurements of the galaxies.

Our detection list is given in Table 4???. Column 1 gives the galaxy ID while 2-3 list the positions at which the source was detected. Column 4 gives the NUV magnitude. Column 5 lists the total blue magnitude where the data come either from Caldwell and Bothun (1987) , Ferguson (1989) or Irwin et al (1990). Columns 6-7 list the measured 2490-B (25-B hereafter) and 1520-B (15-B hereafter) colors. As the blue and UV scale lengths maybe very different we have used the available aperture photometry to construct aperture-magnitude relations to measure the B-magnitude through the aperture used to measure the UV fluxes. We estimate the statistical error associated with this procedure to be 0.1-0.2 magnitudes (some of the aperture photometry is sparse). This error is not large relative to the range of 25-B color. For the case of the FCCB galaxies (which are likely background to Fornax), the UV aperture is several effective radii large and hence 25-B for these objects is a total color, Column 8 lists the aperture radius through which the 2490Å and 1520Å fluxes were measured. Columns 9 and 10 give the 2490Å flux and the measured 1520-2490 color (15-25 hereafter). Note that these colors and fluxes have not been corrected for foreground reddening to Fornax.

A few of the galaxies listed in Table 4???? have individual peculiarities: NGC1387 is at the edge of the field in the NUV image and completely off the field in the FUV. NGC1399 has a star at radius 12.7". For this galaxy, two values for 25-B are calculated. The first uses Ferguson's data to determine the 25-B color through an aperture of diameter 66.2". The second uses Sandage and Visvanathan's (1978) value for NGC1399's B magnitude, and our UV values, both at diameter 15.2". FCCB1374 also has a star in it at radius 6.5". The effective radius for FCCB1374 is given by Ferguson (1989) as 4.3", so we found the colors both at a radius of 4.3" and at 22.8". The blue magnitude of Galaxy X was estimated from

Fig. 3.— The color-magnitude relation for the detected galaxies listed in Table 4???. The three bluest points are suspected to be background to the Fornax cluster.

the optical data. Its overall size and surface brightness are very similar to FCCB 1364.

Of the 27 optically catalogued galaxies which lie in the field, 9 were detected in the NUV but only 5 were detected in the FUV. Table 2 lists those galaxies that are brighter than B_T = 18.0 that were not detected in the NUV or FUV images. None of the galaxies found had $B_{mag} > 18.0$. Of the fifteen galaxies with $B_{mag} \leq 18.0$, six were not found (table 2). FCC 222, the brightest of the 'missing' galaxies, has a spatial position coincident with a notable cosmetic flaw on the detector.

4. Summary Discussion

Our detected sample contains 3 luminous early type galaxies (NGCs 1397, 1399 and 1404), 2 dwarf ellipticals (dEs - FCCs 202 and 207), both of which are nucleated, and 5 galaxies considered to be background based on their small angular size (FCCBs 1237,1353,1364,1374 and Galaxy X). Of these, we believe that the FUV detection of FCCB 1237 and FCCB 1353 confirms their background nature as the measured 15-25 color requires a fairly hot component like that seen in NGC 1399 in which extreme horizontal branch stars are thought to be responsible for this component (see Ferguson et al 1991; Brown et al 1995). For these probable background galaxies, this component is probably not due to EHB stars and is more likely the result of an active nucleus and/or active star formation. The 15-25 color of FCCB 1353 is bluer than that of an O3 star and the morphology of the galaxy suggests its interacting. As this galaxy is at unknown redshift, it is possible that Lyman-α emission is present in the FUV bandpass. Good optical

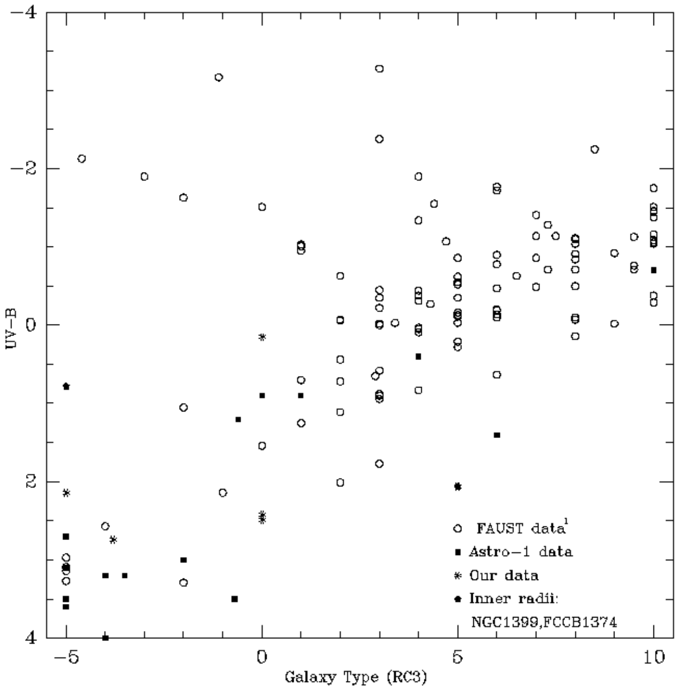

Fig. 4.— UV-B color vs. RC3 galaxy type for all Astro-1 and FAUST data. FAUST data from Dehaveng, et al (1994)[1]. Astro-1 data (not including current sample) from E. Smith (private communication).

spectroscopy of these galaxies is therefore desirable but for our purposes the detection of these objects in the Astro-1 image is again confirmation that optically faint galaxies can be detected through their UV flux. Indeed, it is perhaps telling that a UV imaging study of a nearby cluster has detected a large precentage of background objects.

Figure 3 shows the distribution of 25-B color for our small sample. Similar to the galaxies that comprise Figure 1 1, there is a fairly large range in 25-B color although none of these galaxies has a significant UV excess. This is not surprising as the center of a cluster should contain a sample of mostly non-star forming galaxies. The 25-B colors are fairly constant with aperture with the notable exception of NGC 1399 which is well known to have a UV -excess (see Ferguson et al 1991). There is no evidence that these galaxies tend to get bluer when measured in smaller apertures which would be the case if nuclear UV sources dominated the overall NUV emission. This encouraging result suggests that NUV observations are capable of detecting the underlying stellar population in dwarf galaxies. Indeed, its important to state that initial optical observations of Fornax failed to detect most of the faint dEs in the first place. These were found later using deeper plate material or moderate exposure CCD observations. The fact than a 1000 second exposure obtained with an 18-inch telescope can detect some of these optically faint galaxies is strong encouragement that the galaxy LF, in nearby groups or clusters, can be well sampled by NUV observations. At FUV wavelengths, the combination of reduced detector efficiency and intrinsic galaxy flux means that only either optical bright or very UV bright galaxies can be detected.

Figure 4 shows the NUV-B color as a function of galaxy morphological type both for all Astro-1 UV data (including our sample) and the FAUST data (Deharveng et al 1994). The RC3 classification is used (-5.0 is E0, 1.0 is Sa, etc.). Although taken at different wavelengths ($\lambda_{peak} \approx 1650$ Å, $\Delta\lambda \approx 250$ Å for FAUST and $\lambda_{peak} \approx 2800$Å, $\Delta\lambda \approx 1100$ Å for Astro-1), both data sets show the same increase in color dispersion from late to early types, as is expected (i.e. Donas et al 1987). Clearly, the colors of the galaxies in the Fornax field are not anamolous in any respect.

The stellar population of dEs has been studied extensively at optical and near-IR wavelengths (see Bothun et al 1986; James 1990; Caldwell and Bothun 1987). In those studies there have been occassional suggestions that some dEs, especially the nucleated ones, could be experiencing low level star formation as there are spectral/photometric features which indicate a contribution to the light from youngish stars. In addition, dEs often show the same range of broadband optical and near-IR colors as do Galactic globular clusters. While the UV data presented here does little to address the general nature of stellar populations in dEs there are two comments we can make: 1) On average, O3-O5 stars have 25-B ∼-3.0 and M_{nuv} ∼-9. At the distance modulus of Fornax (m-M = 31.0), a single O3-O4 star would have an apparent NUV magnitude of 22.0; 100 of these stars would have $m_{nuv} = 17.0$. Because galaxies as faint as $m_{nuv} = 18.5$ were detected, we can place a limit that any other dEs in the field must contain fewer than 25 unreddened O-stars in their current stellar population. While this may not be a surprising result, it nevertheless is a relatively strong constraint on low level star formation in these galaxies. 2) The 25-B colors of metal-poor globular clusters range from 0 to 1.2 (see Smith et al 1993). The two bona fide nucleated dEs in this sample are considerably redder than this and have colors that are not significantly different than the two giant ellipticals in the sample. This behavior is considerably different than in the optical where dEs tend to be significantly bluer than gEs. The color-magnitude relation is thought to be driven by metallicity with lower metal abundance systems having warmer giant branches and hence bluer broad-band colors. For some metal poor Galactic globulars, warmer giant branches are known to feed a very blue horizontal branch population. For the dEs in Fornax this is unlikely to be the case as the presence of this population would have produced 25-B colors that are considerably bluer than those actually measured. Moreover, the failure to detect other dEs (see Table 2) suggests that 25-B must generally be redder than 2.5. *It would thus appear that none of the dEs in the Fornax cluster have a significant blue horizontal branch population.* Either these dEs are fairly metal-rich or the second parameter problem, so familiar in the context of Galactic globular clusters, also operates in dEs.

In sum, the 1000 second Astro-1 exposure of NGC 1399 and surrounding galaxies allowed for a weak NUV detection of 9 out of 15 known galaxies which $B_t \leq 18.0$, plus one additional detection of an uncatalogued faint galaxy. While some of these faint galaxies may be background, others are true dwarf galaxies. This straightforwardly shows that optically faint galaxies can be detected at NUV wavelengths using moderate exposure times and small aperture instruments. Based on these data, we would then predict that the longer exposures planned for the NUV camera in the Astro-2 mission would have been quite successful at detecting faint, nearby dwarf galaxies with a substantial probability for serendipitous detections of new objects. Unfortunately, this last statement will have to remain as conjecture. We emphasize that our sample contains mostly non-starforming galaxies and hence the ability for NUV imaging to find faint, star forming dwarf galaxies could be quite high. In fact, we predict that analysis of the Astro-2 fields around bright target galaxies will produce a few serendipitous detections of previously unknown star forming dwarf galaxies. Indeed one such object may have already been found in the Astro-1 exposure of NGC 4258 (Fanelli 1995).

Although our sample size is necessarily limited and our exposure times are rather short, we nevertheless conclude that imaging observations in the VUV are capable of detecting optically faint galaxies. The properties of both dwarf and LSB galaxies thus make them ideal candidates for further UV imaging studies. The low background in the VUV is a real phenomenon which should be duly exploited to more fully discover the population of galaxies that hides in the noise of the terrestrial night sky.

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