A Wide Field CCD Survey for Low Surface Brightness Galaxies:
II. Color Distributions, Stellar Populations and Missing Baryons

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Abstract

We have performed a digital survey for Low Surface Brightness (LSB) galaxies in the spiral-rich Cancer and Pegasus clusters as well as the low density regime defined by the Great Wall. A total of 127 galaxies of angular diameter larger than 15 arcseconds were found with $\mu_B(0) \geq 22.0$ mag/arcsec^2, 119 of which were previously unidentified. Structural parameters ($\mu_{\rm B}(0)$, α, r_{25}, etc) and colors (Johnson/Cousins U,B,V,I, & R, when possible) were determined for all galaxies. Paper I of this series described structural parameters; here we focus the discussion on the stellar populations of these newly discovered galaxies as implied by their observed broad-band colors.

The colors of the survey galaxies range continuously from very blue (U-B=-0.56, B-V=0.37) to very red (U-B=0.65, V-I=2.2), and include a group of old galaxies which show evidence for recent star formation. This survey is also the first to discover a significant population of LSB galaxies which have red colors. Since galaxies must fade and redden, the absence of red LSB disks in previous surveys has been puzzling. Their recovery in this survey suggests that photographic selection from blue plates, which forms the basis of previous LSB surveys, carries with it strong selection effects. The continuous range of colors, from very blue to very red, that we observe for this sample clearly shows that LSB galaxies at the present epoch define a wide range of evolutionary states.

Consistent with other surveys we find a significant number of galaxies with $\mu_B(0) \geq 23.0$ mag/arcsec^2 which suggests that the space density of galaxies as a function of $\mu_B(0)$ is not strongly peaked. To more rigorously test this hypothesis we compare the actual surface brightness distribution from our survey with that from two different types of Monte-Carlo based sky images, one with an underlying flat surface brightness distribution and one with an underlying Gaussian distribution (falling off at 24.0 mag arcsec^{-2}). We show that there is no way of distinguishing between the flat distribution and the Gaussian one as the proper description of the underlying surface brightness distribution for this survey beyond 24.0 mag arcsec^{-2}, in spite of the fact that our survey limit is actually 26.0 mag arcsec^{-2}. This demonstrates that an even deeper and more difficult to obtain isophotal limit is required to more accurately determine the space density of very LSB galaxies as well as to define the faintest possible central surface brightnesses that galactic disks can have.

1. Introduction

That low surface brightness (LSB) galaxies contribute significantly to the total galactic number counts has been well established (McGaugh, Bothun & Schombert 1995, Impey, et al 1988, McGaugh 1996, Bothun, et al 1997). As such, knowledge of the stellar content and evolutionary paths of LSB galaxies is crucial to understanding the formation and evolutionary history of all galaxies. Previous LSB surveys have typically focused on discovery and detection – finding the location and structural properties of LSB galaxies without discerning much about their underlying stellar properties (Davies et al 1989, Schombert et al 1992, Davies et al 1994a, Impey, et al 1996). Previous investigation into LSB galaxies' surface photometry has been limited to a few galaxies (Romanishin, et al 1983, McGaugh & Bothun 1994, de Jong 1995, Sprayberry, et al 1995, de Blok, et al 1995, Knezek 1993). In an attempt to broaden our knowledge of the distribution and stellar content of LSB galaxies we have undertaken a digital survey of select sky regions for LSB galaxies. Once the galaxies are identified, we observe them again through multiple (U,B,V,R & I) filters in order to provide a reasonable color baseline for determining stellar populations. Still, this baseline is limited due to the lack of near-IR photometry which, when combined with optical photometry can help break the age-metallicity degeneracy in optical colors (e.g. Bothun et al 1984). Unfortunately, the near-IR sky brightness is approximately 7-8 magnitudes higher than the near-IR central surface brightness of our sample galaxies which precludes good measurements in this spectral-region at this time. Even at I-band, the S/N of many LSB disks is quite weak.

The results from our survey are presented both here and in a companion paper (O'Neil, et al 1997, OBC from now on). OBC give a complete description of the data acquisition and reduction techniques, as well as the structural parameters ($\mu_B(0)$, radius, α, etc.) for all of the LSB galaxies in our CCD-selected sample. This paper extends OBC by giving all of the available color information for each galaxy and a complete summary of our findings. In Section 2 we briefly describe our observations and data reduction. Section 3 discusses the color data en masse while Section 4 breaks the sample into various color regimes and discusses the properties of the individual LSB disks that occupy these regimes. Section 5 presents a comparison of inner and outer colors to search for color gradients and/or other signals of non-uniformity of the stellar populations in these galaxies. Finally, section 6 examines the possible contribution of LSB galaxies to the overall baryon content of the universe.

At the moment, our newly discovered sample is without redshifts (due to the Arecibo upgrade) and when necessary, distances are assigned assuming that the galaxies are members of the host cluster or structure in which they are found. Previous searches for LSB galaxies in the direction of clusters have concentrated mostly in Virgo (*e. g.* Impey et al 1988) and Fornax (*e. g.* Davies et al 1990, Evans et al 1990, Bothun et al 1991) and those surveys discovered mostly *dwarf* LSB galaxies (*i. e.* those with a scale length ≤ 1 kpc). With the expectation of Davies et al (1989) who searched for LSBs in A1367 (mean velocity $\sim$6500 km sec^{-1}), our search is the only one to concentrate on clusters/structures in the velocity range 4-8,000 km sec^{-1} with the expectation of finding relatively large LSB disk galaxies,

2. Summary of the Filter Observations

All the data was taken on the University of Texas McDonald Observatory 0.8m telescope between 1993–1996 using a Loral-Fairchild 2048x2048 pixel CCD camera with 1.32"/pixel resolution. The data sets consist of three consecutive nights of observation followed by a separation of six months repeated for a total of five data sets. Approximately fifty-four 45'x45' fields were imaged during that time, resulting in a total of 27 degrees^2 of sky being imaged. The fields covered both the Pegasus and Cancer sky regions as well as the area around various (known) galaxies distributed in the Great Wall (Geller & Huchra 1989;, Dell Antonio et al 1996). Six to eight flat field images were taken each night for each filter and were (median) combined to obtain the flat field images for that night's data. The typical seeing disk was 1.5-2.0" during these observations, though we emphasize that in conditions of relatively good seeing the data are rather undersampled. Further details about the reduction procedure can be found in OBC.

Photometric zeropoints for all the data were determined as follows. When conditions were photometric, magnitudes and colors corrected for atmospheric extinction were obtained from standard stars (Landolt 1973,1983) observed through each of the filters. An exception was made for the images in through the R filter, in which case photometric zeropoints were found using the galaxies in Sandage & Visvanathan (1978). Extinction coefficients were determined by observing standard stars over the air mass range 1.0 – 2.2. Galaxies were also observed at air mass ≤ 1.7. The precision of these photometric standards is the lowest in the I-band filter and, in general, the signal-to-noise of the galaxies are also lowest in this filter (due to the increased noise and brightness in the sky background at I-band wavelengths). Under non-photometric but transparent conditions, photometric zeropoints could still be obtained by using the brighter galaxies in Bothun etal (1985) as photometric standards. Those measurements were originally calibrated using the same sets of Landolt standards except in the case of the I-band data where no previous data exists. Hence, determination of I-band data for this survey required photometric conditions. For the few galaxies found in the Great Wall fields, pre-existing I-band data from Dell'Antonio etal (1996) was available to use as a calibration under non-photometric conditions. Typical precision for the I band photometric standards is 0.04 mag, while the secondary calibrators are good to 0.03 mag.

In general, the galaxies contained in Bothun etal (1985) were observed through more than one aperture and only the brighter galaxies were selected to avoid uncertainties associated with centering errors for the fainter galaxies listed in Bothun etal (1985). To determine zeropoints from that data, we obtained (sky-subtracted) fluxes using IRAF's QPHOT procedure in which apertures identical to those of Bothun et al (1985) were used on the CCD data to measure the flux. The multi-aperture extraction of zeropoints, for each filter exhibited r.m.s variations of 0.02–0.03 mag for B,V and R and 0.04 mag for U. As many objects were identified in each field as possible, with a minimum of four standard stars/field and two known galaxy/field (though typically 6-8 standard stars were used and 4-10 known galaxies). The rms scatter for the zeropoints was ± 0.01 - 0.06 mag in each field, with the typical value being 0.03 mag. For the rare occasion the rms was higher than 0.05 mag, the additional error is given in Table 1.

To ensure centering was not a problem with the total colors of both the reference galaxies and the galaxies described in this paper, centers and total magnitudes were found a minimum of three times and the results compared. The r.m.s scatter in zeropoints was 0.02 mag but some particularly amorphous LSB galaxies are prone to a larger error owing simply to the difficulty of determining their center for aperture photometry. These are the cases with the largest total photometric errors and they are so flagged in Table 1. Our total derived photometric errors are due both to the random errors associated with the individual aperture photometry of the LSB galaxy as well as errors in the photometric zeropoints, either from the Landolt stars or from the galaxies listed in Bothun et al (1985). Aside from the occasional large photometric errors due to centering uncertainties, the total error for the galaxy colors is $\leq$0.08 (at worst), and is typically around 0.05 mag. This is sufficient precision to obtain our principle scientific goals. Galaxies with errors larger than 0.1 mag in any one color are excluded from any of the color-color plots presented later.

U,B and I filters were used for the 14–19 October 1993, 7–12 March 1994, 29 October – 3 November 1995, and 12–14 March 1996 data runs (runs 1,2,3, & 5 respectively). The U filter was also used during the 26–30 October 1995 run (run 4). A V filter was used during runs 1,4 and 5, and an R filter was used during run 4. The seeing through the I filter was particularly poor on the night of 9–10 March 1994 and those images were discarded. Typically, three images were taken through both the B (exp. time 600s) and U (exp. time 900s) filters, and one was taken in V (300s), I (120s), and R (180s). Multiple images were averaged to eliminate extraneous noise.

The typical sky brightnesses through the various filters are given in Table 3. The sky was often brighter than would have been ideal due to the presence of thin cirrus clouds during many of our observations (hence requiring the use of previously observed galaxies in the field to act as photometric standards). On average we were able to detect LSB galaxies down to $\mu_B(0)$ = 25.5 mag arcsec^{-2}, or 3% of the sky background. Surface brightness profiles could accurately (error $\leq$0.25 mag arcsec^{-2}) be measured to 27.5μ_B , or 0.5% of the sky background. To be included in our final sample, each galaxy had to be detected in the B,V and R filters. Since images of LSB galaxies are difficult to print, we refer the reader to http://guernsey.uoregon.edu/ ˜ karen where all the digital data is reproduced.

3. The Data

Table 2 lists the color information for most of the galaxies in our survey. The data is given as follows: Column 1 provides the galaxy's identification; columns 2–5 list the blue magnitude and the U-B, B-V, & V-I colors for the galaxies within r=5"; columns 6–9 give the blue magnitude and colors for the galaxies at the maximum usable radius in each color (the radius before which the magnitude error in either color exceeds 0.25 mag); column 10 lists each galaxy's maximum useful radius in the blue (again, radius before which the magnitude error exceeds 0.25 mag). (When no information was available on a galaxy's V magnitude the colors listed in columns 5 and 9 are the B-I colors.)

The galaxy identification given in column 1 is the identification used by OBC. The majority of the galaxies in this survey (92%) were previously unidentified. In the rare case the galaxy has been previously detected that name, along with the RA and Dec of all the galaxies listed, is given in Tables 2 and 4 of OBC.

The magnitude and color information given in columns 2–5 is the galaxies' magnitude through each filter at the r$_{major}$ = 5" isophote. The galaxy's peak intensity, in each color, was chosen as the galaxy's center when possible. Since none of these galaxies have bright cores, we do not expect this photometry to be compromised by the effects of seeing or varying point-spread-functions across the frame. If the galaxy had no obvious peak intensity it's luminosity weighted center was chosen. The errors for the color in these columns is occasionally higher than the error for the total color and magnitude for the same galaxy due to difficulties in determining the center. This problem occurs primarily with the ultraviolet filter, since the galaxies were typically very faint in those images and thus the galaxy's peak intensity and physical center were not always obvious. Galaxy colors and magnitudes were corrected for Galactic extinction but not for either inclination or redshift.

The magnitudes and colors given in columns 6–9 of Table 2 were calculated through finding the radius at which the magnitude error reaches 0.25 mag. The colors were then found by using the magnitudes at the smallest maximum radius for each color pair (i.e. for U & B or V & I). In most cases the maximum radii for each color were similar, and close to the r$_{max}$

given in column 10. The exception to this, when the maximum radius in one color was much smaller than in it's companion color, was due to the galaxy having a particularly low signal-to-noise ratio in that filter. This problem arose more frequently in the U-B colors than in any other.

The errors for Table 2 are all less than 0.05 mag, unless otherwise given. Error for colors involving the infrared filter is high because of the large amount of background sky noise through that filter and the lower precision of the available I-band photometric standards. Finally, column 10 gives the radius (through the blue filter) at which the magnitude error reaches 0.25 B mag. Total B magnitudes are determined with this radius.

Table 3 gives the color information for the galaxies in fields taken 10/26/95–10/30/95. The data in Table 3 is is similar to that found in Table 2, only the magnitudes (both at 5" and the total magnitude) are from the V filtered image, the colors listed are u-v (columns 3 and 6) and V-R (columns 4 and 7), and the r_{max} is for the maximum radius through the visual filter. (No data was available through the blue filter for these galaxies.) All the colors and magnitudes were obtained through the same methods used on the galaxies listed in Table2. All the errors for the colors are given. (Errors are higher than for the other data due to a deficiency in the number of comparison galaxies used in obtaining a photometric zeropoint and the presence of bright galaxies within each field.)

4. Colors

The color distributions for the galaxies in this survey, as well as the color distributions from other LSB galaxy catalogs, are shown in Figure 1. (The other LSB catalogs used are de Blok, et al 1995, Sprayberry, et al 1995, McGaugh, 1992, Bothun, et al 1991, Impey, et al 1988, Caldwell & Bothun 1987, and Romanishin, et al 1983.) While Figure 1 shows there to be considerably overlap in the color distributions, our survey reveals a contingent of fairly red LSB galaxies. In fact, this is the first survey to have discovered this population of red LSB galaxies a point that we will return to later. The apparent difference in mean $\mu_B(0)$ values is due to our brighter cut-off (22.0 $\mu_B(0)$ compared to 23.0 $\mu_B(0)$ for most LSB galaxy surveys) and not to any real difference in $\mu_B(0)$ spreads. (Our cutoff at 22.0 $\mu_B(0)$ was chosen simply because of the large number of previously uncatalogued galaxies found in our survey that were in the 22.0–23.0 $\mu_B(0)$ range.)

The average magnitude and colors for the galaxies in our survey are $\langle$ B$_{\rm mag}$ $\rangle$ = 17.68 ± 0.19, $\langle$ U-B$\rangle$ = 0.082 ± 0.034, $\langle$ B-V$\rangle$ = 0.790 ± 0.032, and $\langle$ V-I$\rangle$ = 0.935± 0.054, but they have ranges of 13.1 $\leq$B$_{\rm mag}$ $\leq$20.5, -0.73 $\leq$U-B $\leq$0.96, 0.12 $\leq$B-V $\leq$1.8, and 0.15 $\leq$V-I $\leq$1.6. The average values thus are not representative of the galaxies as a whole but instead the entire range of LSB galaxy colors needs to be examined to understand the galaxies' nature. Figure 2 show the distribution of galaxy colors and central surface brightness ($\mu_B(0)$) for the three sky regions studies in this survey (Cancer cluster, Pegasus cluster, and the Great Wall region). As can be seen, no difference exists between the three samples. Due to the nature of these galaxies, as well as the low resolution (1.32"/pixel) of the survey, no comparison can be made between the galaxy's colors and their morphological type. Furthermore, most of the galaxies are amorphous blobs with little or no spiral structure and hence do not lend themselves easily to morphological classification.

4.1 The Very Blue

The existence of very blue LSB galaxies has been previously documented (i.e. McGaugh & Bothun 1994, de Blok, et al 1995, Impey, et al 1996) and is important primarily because of the restrictions they put on the star formation history of LSB galaxies. The simplistic explanation – that LSB galaxies are merely faded remnants of HSB galaxies – is quickly eliminated by the existence of these very blue LSB galaxies. The galaxies in the bottom left of 1(a) & (b) have colors of U-B< -0.2, B-V< 0.6, and V-I< 1.0, whereas the average colors of E0/S0 galaxies (good examples of old stellar populations) are U-B=0.54, B-V=0.96 (Tinsley 1978). Late type spiral galaxies, on the other hand, do have colors similar to both the bluer LSB galaxies in our survey as well as to the colors of LSB galaxies found in other surveys. Sc or later spiral galaxies with active star formation typically have colors in the range $0.65 \geq$ B-V ≥ 0.35, $-0.2\leq$ U-B ≤ 0.4 (Huchra 1977, Bothun 1982), with mean values $\langle$ B-V$\rangle \approx 0.50$, $\langle$ U-B $\rangle \approx -0.20$ (Bothun 1982) and $\langle$ V-I$\rangle \approx 1.0$ (Han 1992). These colors encompass most of the very blue galaxies in our survey, and come close to matching the LSB galaxy colors found by McGaugh & Bothun (1994) (median colors of $\langle$ B-V $\rangle$ = 0.44, $\langle$ U-B $\rangle$ = -0.17, and $\langle$ V-I $\rangle$ = 0.89) and Romanishin et al (1983) (average colors of $\langle$ B-V $\rangle$ = 0.43± 0.04, $\langle$ V-R $\rangle$ = 0.60± 0.02). Of course, LSB disk galaxies, on average, have factors of ten lower star formation rates (SFRs) than Sc galaxies (i.e. McGaugh & Bothun 1994, McGaugh & de Blok 1997).

The issue here is how to best explain these very blue colors in galaxies with very low SFRs. One explanation for the very blue LSB galaxies could be their low metallicity. McGaugh (1994) has shown that LSB galaxies typically have low metallicities, approximately 1/3 the solar metallicity. This could lead to a bluing of the galaxies' colors. A comparison with the colors of globular clusters (($\langle$ U-B$\rangle \approx$0.1, $\langle$ B-V$\rangle \approx$0.65, $\langle$ V-I$\rangle \approx$0.95 (Reed 1985)), however, shows that these very blue LSB galaxies are actually *bluer* than very metal poor globular clusters. Thus, although low metallicity may play a role in the color of very blue LSB galaxies, it can only account for part of the reason (see McGaugh & Bothun 1994, de Blok, et al 1995). The simplest surviving theory to explain the very blue LSB galaxies is that the galaxies have a young mean age.

If our sample of LSB disks are at the redshifts of their host clusters, then their typical luminosity is $L_B \sim 10^{10} L_\odot$. The constant SFR models of Larson & Tinsley (1978) generally yield colors of B-V = 0.45 – 0.50 and U-B = -0.20 – -0.10 for star formation that has occurred over a 5-10 Gyr period. That model, when applied to HSB galaxies with observed present day SFRs of 1–2 $M_\odot$ yr^{-1} successfully predicts both the color and the luminosity of the galaxy. For our LSB disks with similar color and luminosities, the present day SFR is extremely low and if maintained for 5-10 Gyr could not possibly account for all the stars present in these galaxies. This would seem to require that star formation in these systems occurs in sporadic bursts perhaps superposed on a constant, albeit low, SFR (see also de Blok et al 1995). A simple model shows that the addition of a starburst involving 10% of the galaxy's total mass, a constant SFR, and lasting 10^7 years, can lower the galaxy's colors by as much as Δ(B-V)=-0.1, Δ(U-B)=-0.2 while only increasing the central surface brightness of the galaxy by $\Delta\mu(0)$ = -0.6 mag arcsec^{-2}(see O'Neil & Bothun 1997). Under this model, one expects significant UV flux for these galaxies, both from the burst population and from the underlying extremely blue horizontal branch metal poor stars. When redshifted into the blue/visual filter, these galaxies could be the local counterparts to the very blue, high redshift galaxies found in recent surveys (i.e. Ferguson & McGaugh 1995). Indeed, O'Neil et al (1996) found some examples of low luminosity galaxies in the Fornax cluster which could be detected in the vacuum UV.

Good examples of very blue LSB galaxies in our survey are P6-2, N1-1, N3-3, and N1-3. P6-2 is a classically young galaxy. With colors U-B=-0.168, B-V=0.613, P6-2 is spectrally similar to a Sc/Sd galaxy (Guiderdoni & Rocca-Volmerange 1988, Huchra 1977). Its low V-I value (V-I=0.517) indicates P6-2 lacks a significant population of old stars, being comprised of less than 20% of M0 and later stellar types (Allen 1973).

N1-1 and N3-3 have U-B=-0.53 and -0.56, respectively, and N3-3 has B-V=0.38 (± 0.1). With these colors neither galaxy can have more then 20% K0 and later star types, and most likely have less than 10% K0 and later type stars. With U-B=-0.73, N1-3 is an even more extreme case. Without any other colors it is difficult to say more about N1-3, but clearly all three of these galaxies are younger than P6-2 and must be experiencing a relatively intense period of star formation. That the galaxies remain LSB during this evolutionary phase ($\mu(0)$ = 22.85, 23.40, 24.60 mag arcsec^{-2}for N1-1, N3-3, and N1-3, respectively) indicates the bursts are not centrally concentrated but spread diffusely across the galaxies. This of course is not consistent with the conventional view that a starburst galaxy is experiencing a globally high rate of star formation due primarily to activity in the very dense molecular cloud medium located near the center of the galaxy.

4.2 The Very Red

A new and significant discovery in this survey are very red LSB galaxies. As seen in Figure 1, before this study few LSB galaxies found had U-B $>$ 0.3, B-V $>$ 0.8, and no survey had found LSB galaxies with U-B $>$ 0.4 and B-V $>$ 0.9. These red colors are unlikely to be the result of photometric errors and/or the presence of strong bulges. The red colors are also unlikely to be the result of photometric errors and/or the presence of strong bulges. The red colors are also unlikely to be the manifestation of large internal reddening. In fact, there is rather little evidence of dust in LSB disks in general as most LSB disks have quite blue colors with no conspicuous dust lanes. Combined with their low metallicity and lack of IRAS detections (see Schombert et al 1992), the observations argue for low dust content in general. This may reflect both the relatively unevolved state of LSB disks and/or a deficiency of massive stars born in each, sporadic star formation event. In figure 3 we plot color versus inclination for all the galaxies in our survey to perform another simple test to determine dust content. In the optically thin case, if the galaxies had a substantial dust content, then, as the inclination increased for the galaxy so would the absorption of light and optical wavelengths due to the increased path length through the dusty disk. This light would then be re-emitted in the infrared, resulting in an apparent reddening of galaxies with increasing inclination. Figure 3, however, shows no relation between color and inclination, consistent with LSB galaxies being (relatively) dust-free.

This lack of detected red LSB galaxies has been a concern in the past (i.e. McGaugh & Bothun 1994) because without them it appears LSB galaxies have colors equivalent only to Sc and later galaxies and do not cover the full spectrum of HSB galaxy colors – that is, it appears *no* faded LSB galaxies exist at the present epoch. Since at some future epoch when star formation ceases, all galaxies will fade into LSB objects, the lack of this process occurring now, given the low fractional gas contents of many galaxies, is a bit disconcerting. Indeed, McGaugh (1994) has argued that the photographic selection process has prevented red LSBs disks from being detected previously so perhaps the CCD selection criteria, defined by simultaneous detections in the B,V and R filters, has effectively corrected for this selection effect. Possibly, as argued below, LSB disk galaxy evolution is accelerated in clusters and hence clusters contain more red LSB disks than blue LSB disks, although in general this is not the case for HSB disks in spiral-rich clusters (*e. g.* Bothun et al 1982) nor really for dwarf galaxies in the Fornax cluster (*e. g.* Evans etal 1990, Bothun et al 1991).

To test if the selection through multiple filters influenced our finding of red LSB galaxies, we compared the (B-V) color distribution for those galaxies within 1σ of the average $\mu_B(0)$ against the the (B-V) colors of the galaxies within 1σ of $\langle\ \mu_V(0)\ \rangle$. Both distributions had B-V = 0.72 ± 0.1, and a mean value of B-V = 0.69. Thus, had images only been available in one of the two filters, then, (B or V), the same overall color distribution, including the very red LSB galaxies, would still have been found. (This test was not performed through the R filter because of the smaller number of galaxies observed through that filter and the larger photometric uncertainties associated with the R-band observations; however, there is also no correlation between R-band central surface brightness and B-V color).

As mentioned earlier, the average colors of E0/S0 galaxies are $\langle$ U-B$\rangle$ =0.54, $\langle$ B-V$\rangle$ =0.96 (Tinsley 1978). The galaxies in the upper right corner of Figure 1(a) & (b) include colors from 0.8$\leq$B-V $\leq$1.2, 0.4$\leq$U-B $\leq$0.8, and 1.0$\leq$V-I $\leq$1.7, showing that the colors of the very red LSB galaxies in our survey are similar to the colors of some of the oldest galaxies. Larson and Tinsley (1978) approximate these colors with their model of a galaxy which formed stars for only the first 10^7 years, and has been quiescent for it's remaining 20 Gyrs. (For this model they obtain U-B=0.74, B-V=1.02). It is quite likely, then, that these galaxies are also the result of a bursting SFR. Unlike their blue counterparts, though, these galaxies underwent starburst early in their existence, consuming most of the galaxies' gas and leaving them with only an old stellar population. In fact, this is the expected route to low disk galaxy surface brightness but until now, it had not been observationally detected.

Good examples of LSB galaxies with old stellar populations are C1-2, C11-1, C11-3, and C4-5. C1-2, C11-1, and C11-3 have similar colors - C1-2 has U-B=0.66, B-V=1.12, and V-I=1.14, C11-1 has U-B=0.66, V-I=2.19, and C11-3 has B-I=2.61 – all showing an old stellar population. These colors are slightly redder than Larson and Tinsley's (1978) old starburst galaxy model, indicating the galaxies may be older or have undergone a shorter era of star formation than the galaxy in Larson and Tinsley's model. Also, Larson and Tinsley do not add any corrections for the chemical composition of their model galaxy, an omission which may account for the color discrepancy. C4-5 has U-B=0.956, which is considerably redder than most E0 galaxies and is one of the reddest galaxies ever measured (provided C4-5 is at low redshift).

4.3 The Rest

Naturally, the rest of the galaxies in our survey fall somewhere between the last two extremes – neither consisting of only a young, blue population nor containing only old, red stars. These galaxies fill in the gap between the very blue LSB galaxies and the very red LSB galaxies, showing that we are not merely seeing two distinct galaxy groups - a group of very young, LSB galaxies and a group of very old, faded galaxies - but instead that LSB galaxies cover the entire HSB color spectrum.

One significant group of galaxies have colors U-B$<$ -0.2, B-V$>$ 0.8, and V-I$<$ 1.0, corresponding to primarily young to 'middle-aged' (A0–G8) stars and lack a large population of very old, red stars. The colors of these galaxies are reproduced by Guiderdoni & Rocca-Volmerange (1987,1988) (GR from now on) for young Sc/Sd galaxies. GR obtains the colors U-B=-0.18 - -0.27, B-V=0.75 - 0.88, and V-I=0.91 - 1.00 for Sc/Sd galaxies 11.5 – 11.8 Gyrs old (using GR's values of h_0=0.5 and Ω=0.1). GR assumed the galaxies would have a heavy element fraction of Z=0.02, an unrealistic assumption for most LSB galaxies. McGaugh (1994) gives LSB galaxies a heavy element fraction of Z$<$ 30% $Z_\odot$, or Z$<$ 0.01. Reducing the metallicity of the galaxies in GR would primarily reduce their values for V-I, which follows the trend of the galaxies in our survey quite nicely. As the actual age of these galaxies is presumably similar to the age of all the other galaxies in the various clusters (i.e. Pegasus, Cancer), linking them with galaxies only 11.6 Gyr old merely indicates they have a lower overall SFR than their red counterparts.

This group of galaxies, which includes P1-6, P9-1, P1-2, N10-2, C5-5, and A1-1, is well represented by galaxies which have already experienced their primary phase of starburst but have not completely left their star formation era. These galaxies most likely represent the next evolutionary phase for the very blue LSB galaxies mentioned earlier.

The other interesting galaxy group consists of galaxies whose B-V and V-I colors indicate a large, old stellar population, yet whose U-B colors expose a population of young stars. That is, they appear to be old galaxies currently undergoing a small yet significant burst of star formation. A few good examples of this galactic group are P9-4 (U-B=-0.158, B-I=2.570), C5-3 (U-B=-0.427± 0.2, B-V=1.177± 0.05, V-I=1.325± 0.1), U1-8 (U-B=0.307, B-I=2.787), and P10-1 (U-B=0.262, B-I=3.574± 1.). In all cases the very red V-I or B-I colors can only be obtained by a significant population of K0 and later stellar types, yet the U-B colors in this group are similar to a Sc or earlier galaxy (Huchra 1977). We plan to do Hα imaging to these samples to identify H II regions for spectroscopy to determine abundances and star formation rates.

Preliminary results from the models of O'Neil & Bothun (1997) shows that if 15% of a galaxy undergoes a starburst, the galaxy's U-B color will change by -0.6 mag while it's B-V and V-I colors change by only -0.3 and -0.15 mag, respectively. If the starburst is evenly distributed throughout the galaxy the central surface brightness will increase by roughly 1 mag arcsec^{-2}. Realistically, though, it is likely tidal interactions will result in local compressions in the LSB galaxy's gas (Mihos, et al 1997). In this case, the color changes would occur in outer annuli and the galaxy's central surface brightness would show a smaller increase. Note that rotation curve data obtained by de Blok et al (1996) indicates that LSB disks are dark matter dominated at all radii and hence are likely to be quite stable to tidal disruption so repeated encounters in the cluster environment are possible. In addition, most LSB disks are in an environment that would promote only weak tidal interactions (Bothun et al 1993).

5. Core vs. Outer Annuli Colors

LSB galaxies generally lack the distinct bulge/disk regions evident in many of HSB galaxies. This amorphous nature of LSB galaxies has been noted by McGaugh, et al (1995) (amongst others) who showed the typical bulge to disk ratio of a LSB galaxy to be $\leq$0.1. OBC confirm this by noting that the surface brightness profiles of the galaxies in this survey are usually well described by one (exponential) curve thereby eliminating other structural components (i.e. a central bulge).

The lack of separate bulge/disk components for the galaxies in our survey is evident also in Figure 4, which shows the color of the inner 5" of all the galaxies in our survey against the galaxies' outer annuli (r_{max} - 5"). For all four the colors shown (U-B, B-V, V-I, & B-I) the difference between the colors of the inner and outer regions of the galaxy is small. Were the colors of the core and outer regions part of two separate (bulge & disk) stellar populations the data would be offset either below the x=y line (if the galaxy cores tended to contain older, redder stars) or above it (if the galaxy cores tended to contain younger, bluer stars).

Having roughly the same values for the inner and outer galaxy regions in the B-I and V-I colors is a good indication that any age or metallicity gradient is either small or zero. Both elliptical and spiral HSB galaxies usually have older, redder stars at their core, and the outer regions of the galaxies are much younger and bluer. This is generally understood in the context that the star formation rate depends on the mass density as ρ^n (where n = 1–2) and hence proceeds at a higher rate in the inner, denser regions of galactic disks. It is not at all clear, given the lack of evidence for molecular clouds and dust, that LSB disks would follow the same star formation rate dependence on gas density although there are some examples of LSB disks that do have well-defined color gradients. In general, these LSB disks are the ones with the most well-defined spiral structure. For instance, de Blok, et al (1995) show that the colors of both F561-1 and UGC 128, two LSB galaxies which show (faint) spiral structure, are significantly redder in the galaxy core compared to the outer annuli by 0.4 – 0.6 in B-R. A small minority of the galaxies in our survey also exhibit a difference of roughly 0.5 mag in U-B, B-V, and V-I between their core and outer annuli. Typically, though, the galaxies in our survey are amorphous blobs, devoid of obvious structural components. The less dense nature of the LSB galaxies is the most likely cause of the color uniformity in V-I and B-V – lacking the mass to form a definitive core, which would in turn trigger star formation in that core and form a population of older galaxies, the LSB galaxies in our survey appear to have a uniform stellar age across the disk.

Unlike the other colors, though, the U-B graph shows the outer annuli to be considerably bluer than the inner galaxy regions. This trend is evident both in the average values of the two galactic sections ($\langle$ U-B $\rangle$ = 0.27 ± 0.06 for the core and $\langle$ U-B $\rangle$ = 0.08 ± 0.03 for the outer annuli) and in the fact most of the data points would lie below an x=y line. A difference of almost 0.2 in the regions U-B colors, combined with the smaller difference in the regions B-V colors ($\langle$ B-V $\rangle$ = 0.76 ± 0.05 for the core and 0.79 ± 0.04 for the outer annuli) can result from a brief ($2\text{x}10^7$ year) burst of star formation (Larson & Tinsley 1978) in the outer galaxy regions. Thus although the B-I, and V-I colors suggest a similar age throughout each galaxy, the U-B (and to some extent B-V) colors suggest that the outer regions are undergoing or have recently undergone a burst of star formation not shared by the inner regions. Again, mild tidal interactions could account for this starburst activity. Mihos et al (1991) showed that the larger the separation between the interacting galaxies the smaller the probability the starburst is centrally concentrated. Providing the closest approach between the galaxies is no less than 35kpc, a passing galaxy could easily trigger a small starburst in the outer disk while leaving the inner core virtually untouched. In this case, the appearance of a few newly formed stars would mostly drive the U-B colors blueward, in agreement with the observations.

One prominent exception to the amorphous shape of most LSB galaxies is P1-7. P1-7 clearly shows a bright central bulge and a nice spiral structure. Unlike both it's HSB counterparts and the more impressive (and massive) Malin 1 cousins, though, P1-7 does not show any distinct bulge and disk components in it's surface brightness profile (see OBC), nor does it exhibit magnitude or color differences between the two components significantly different from the other LSB galaxies in this survey. The color profile of P1-7 shows it to be clumpy in the inner 5" (the 'bulge' region) and then it smoothes out, typical of a galaxy whose inner region is not one large bulge but is instead clumped into small stellar groups, thereby distinguishing even P1-7's inner bulge from it's HSB counterparts. The face-on spiral structure of P1-7 classifies it as a Sd/Sm type galaxy, although it's colors indicate it is slightly bluer and metal poor than the typical HSB Sd/Sm galaxy (Huchra 1977).

6. The Flat Surface Brightness Distribution?

In 1970 Freeman found that all spiral galaxies have a narrow distribution of central surface brightness centered around $\mu_B(0) = 21.65 \pm 0.3$ mag arcsec^{-2}. Were his finding correct, the only factor in determining a galaxy's total luminosity, and whether a galaxy is included in a survey, would be galactic size. Freeman's result would also place stringent restrictions on a galaxy's mass-to-light ratio, initial angular momentum, and star formation history, restrictions for which no physical basis has been found. Since his result was published, though, much work has been done to show 'Freeman's law' is due to selection effects and not to an intrinsic property of spiral galaxies (i.e. Disney 1976, Disney & Phillipps 1983, Phillips et al 1993, Davies et al 1994b, McGaugh et al 1995b, Bothun et al 1997). But how extreme these selection effects are is still a matter of debate (see Driver and Phillips 1996).

At issue is the apparent flatness of the $\mu_B(0)$ vs space density diagram first presented in McGaugh et al (1995a) and later confirmed by Sprayberry et al 1996 and Dalcanton et al (1997b). McGaugh, et al 's results follow from the assumption that scale length and central surface brightness are uncorelated. leading to significant volume corrections. The noncorrelation of scale length and central surface brightness is well confirmed by the data (i.e., OBC; van der Kruit 1986; McGaugh & Bothun 1994) and McGaugh etal's results have since been reconfirmed (i.e., Sprayberry et al 1996 and Dalcanton et al 1997a). Extant data shows approximately equal numbers of disk galaxies, per magnitude bin, with $\mu_B(0)$ in the range 22.0 –25.0, with no evidence of a decrease in number density with lower surface brightness out to $\mu_B(0) = 25.0$. Such behavior has significant implications with respect to the missing baryon problem first emphasized by Persic and Salucci (1992). In order to determine how robust the results of McGaugh et al (1995b) and Dalcanton et al (1997b) are we have analyzed simulated data to determine the efficiency which LSB galaxies can be recovered from the noisy background of the night sky since the largest bias against finding an equal number of LSB and HSB galaxies during a survey, if equal numbers exist, is the brightness and noise of the sky background.

To determine how strongly the sky background would influence a survey such as ours, in which the galaxies all presumably lie within a structure (cluster, wall, supercluster) and thus at roughly the same distance, we made and analyzed Monte-Carlo type simulations of the night sky with two different underlying galaxy central surface brightness distributions – one flat and one Gaussian. The sky background for the simulations was 21.76 ± 0.04 mag arcsec^{-2}, the average value for our survey (through the B filter). Each image was 800 x 800 pixels, with a resolution of 1.0 arcsec/pixel (near the survey value). The number of stars/frame was 250 ± 20, and the 100% enclosed light stellar diameters were 20.0 ± 10.0" with peak intensities of 40 ± 40 counts/pixel. Azimuthally averaged star intensities mimicked the measured PSF and fell off roughly as $r_{pix}^{-}2$ where r_{pix} is the radius in pixels from the central pixel. The number of galaxies per frame was 17 ± 1 and each galaxy has $\alpha = 6.5 \pm 4$” (e.g. 1-4 kpc) and $i = 50 \pm 10^\circ$. All values were chosen to mimic the values found in our survey images. We did not extend the angular size range of our simulations to values significantly outside the observed limits of our survey.

The galaxies were given an exponential profile of

$$\mu(\mathrm{r}) \;=\; \mu_0 \;+\; 1.086\frac{\mathrm{r}}{\alpha} \tag{1.1}$$

where μ_0 is the central surface brightness of the galaxies in mag arcsec^{-2}and α is the scale length in ”. Half the galaxies (chosen randomly) were given a bright central core defined by a de Vaucouleurs r$^{1/4}$-type profile with $\mu_0 = \mu_0$ (disk) + cbr mag arcsec^{-2}, where cbr=1.5 ± 0.5. Surprisingly, altering whether or not the LSB galaxies (those with μ_0 (disk) $\geq$23.5 mag arcsec^{-2}) were allowed to have a bright core had no discernible effect on the distribution of galaxies found.

The underlying surface brightness distribution for the simulations was varied between two different sets of models. In the first set (A) the images were given a flat surface brightness distribution from 21.0 mag arcsec^{-2}$\leq\mu(0)$ $\leq$30.0 mag arcsec^{-2}, and an abrupt cut-off at both ends. In the second set (B) the underlying surface brightness distribution was Gaussian, with $\mu_0 = 21.65 \pm 2.1$ mag arcsec^{-2}and an abrupt cut-off again at $\mu(0)$ $\leq$21.0 mag arcsec^{-2}. (Since we are only interested in the galaxies with $\mu(0)$ $\geq$22.0 mag arcsec^{-2}, the cut-off at 21.0 mag arcsec^{-2}does not affect the results.) The final (underlying) surface brightness distributions are given in Figure 6a. Again, the surface brightness distribution was picked to mimic our survey data.

Between 12 and 20 simulations were run for each data set (A & B). Each image was then scanned by eye to identify all galaxies in the image. To eliminate bias by the observer the simulations were viewed independently by two of the authors (O'Neil and Schombert) and the list of galaxies found were compared. No significant differences were found. An example of one of the fields (with a flat underlying central surface brightness distribution) is shown in Figure 7. All the galaxies found by the authors have a white circle drawn around them, while those galaxies not found by the authors have a black circle drawn around them. Parameters for these pseudo-galaxies in Figure 7 are given in Table 4

Figures 6 b & c show the observed central surface brightness distribution for the Texas data (this survey) and for both simulated data sets (A & B). The results of the KS test run on the cumulative frequency distribution of $B\mu(0$ showed that there was no significant difference between the Texas data and the Gaussian surface brightness model (model B, Figure6c). The formal difference in the KS statistic D_{max} is slightly larger in the case between the data and the flat surface brightness model (model A, Figure6b) but the difference is still not significant. The sky images in the simulations were ideal – there was no variance in sky brightness between sky images, all the pseudo-galaxies were symmetric disks (real LSB galaxies tend to be amorphous blobs), and there were no ghost images, CCD flaws, cosmic rays, or bad pixels. If the non-ideal conditions present for real data could be incorporated into our simulations, the difference between model A's distribution and the Texas data would disappear.

The only conclusion which can be drawn from our simulations is that there is no way of distinguishing between the flat distribution and the Gaussian one as the proper description of the underlying surface brightness distribution for this survey beyond 24.0 mag arcsec^{-2}. in spite of the fact that our survey limit is actually 26.0 mag arcsec^{-2}(4.5 mag arcsec^{-2}fainter than the sky) Put another way, we have no way of knowing whether the observed fall-off at $\mu_B(0) = 24.5$ mag arcsec^{-2}in this galaxy survey is because the underlying surface brightness distribution extends only to 24.5 mag arcsec^{-2}or if the underlying surface brightness distribution is flat out to $\mu_B(0) = 26.0$ mag arcsec^{-2}(or beyond), and we are limited by observational selection effects. Were the sky fainter, or the LSB galaxy finding techniques better, we would be able to re-survey galaxy clusters and discover if the same surface brightness distribution is found as was reported in OBC, which would indicate a true cut-off in the allowed galaxy central surface brightness. On the other hand, if improved survey techniques simply find a flat distribution, again down to the survey limits, we would still be stuck wondering whether we once again had found a limiting surface brightness for clusters or if we were merely viewing selection effects. At this juncture, though, we can only conclude that a flat surface brightness distribution does exist in clusters through 24.0 mag arcsec^{-2}, and that clusters contain some LSB galaxies to at least 26.0 mag arcsec^{-2}. It should be noted, however, that the amorphous nature of LSB galaxies may aid in their detection over the very smooth pseudo-galaxies in this simulation.

We emphasize that previous wide field studies have successfully found LSB galaxies with $\mu_0 \geq$24.0 mag arcsec^{-2}(i.e. Schombert & Bothun 1988, Schombert et al 1992, Schwartzenberg et al 1995, Sprayberry, et al 1997, Dalcanton et al 1997b). When combined with the fact that each time a survey has been able to probe for lower surface brightness galaxies they have been found, strongly suggests that surface brightness selection effects persist (see also Impey and Bothun 1997). The underlying surface brightness distribution, and thus the number density of galaxies in the universe ($\phi(0)$) would then be flat through at least 27 - 28 mag arcsec^{-2}. Whether the Sloan Digital Sky Survey has the sensitivity to test this hypothesis is not clear at this time.

7. Summary

Our LSB galaxy sample has been primarily selected from spiral-rich galaxy environments (in the redshift range 4-8,000 km sec^{-1}) and, unlike previous samples, these LSB galaxies cover a color spectrum from the very blue *through the very red.* The very blue galaxies are important not only as further indicators that LSB galaxies are not merely faded HSB galaxies, but also they may be the local counterparts for the distant faint blue galaxies found in recent surveys (i.e. Ferguson & McGaugh 1995). That we have finally discovered very red LSB galaxies is very significant – it shows LSB galaxies fully cover the same color spectrum as HSB galaxies. While the lower surface mass density of LSBs causes them to evolve more slowly, it is possible that environment, and more specifically tidal interactions in loose clusters can speed up the evolutionary process. The red galaxies in our sample may therefore be examples where tidal interactions between neighboring galaxies has caused them to age more quickly than their bluer, presumably more isolated counterparts.

However, this survey has also discovered a significant number of LSB galaxies which have fairly red background colors (presumably due to fading) but which are currently undergoing another small burst of star formation which pushes their U-B color blueward. As these galaxies likely have a mass surface density smaller than their HSB counterparts, their current burst of star formation is probably not due to central infall of gas due to self-gravity but again is probably due to external triggering indicating that environmental influences are still occurring.

In general, the LSB disks galaxies found in this survey lack bulges and are structurally defined by an exponential disk. Morphologically, the LSB "disks" are mostly amorphous with weak or non-existent spiral structure (again the reader should consult the image gallery at http://guernsey.uoregon.edu/˜karen). Typically, we do not detect any significant difference in color between the inner and outer regions suggesting a relatively uniform mean stellar age distributed throughout the system. In addition, there is no observed relation between galaxy color and inclination which is consistent with a low dust content for these systems. That is, the red disks are not preferentially more inclined than the blue ones.

Finally, via Monte-Carlo simulation we have tried to recover the observed distribution of disk central surface brightnesses in our survey. This issue pertains directly to the missing baryon problem as discussed in Impey and Bothun 1997 and briefly summarized here. Walker et al (1991) use the observed abundances of light elements (^{2}H,^{3}He, ^{4}He, and ^{7}Li) and the standard cosmological model to estimate the primordial abundances of the light elements and thus to provide a limit for the present day nucleon to photon ratio (2.8 $\leq$(n_b/n_γ) x 10^{10} $\leq$4.0). With those limits on n_b /n_γ, the limit on the density of baryons in the universe is 0.010 $\leq \Omega_b h_{100}^2 \leq$0.015. ($\Omega_b = \rho_{\rm baryons}/\rho_{\rm c}$, with $\rho_{\rm c} = 3{\rm H}_0^2/8\pi{\rm G}$.) An inventory by Persic and Salucci (1992), however, found 0.0028 $\leq \Omega_b \leq$0.0037 (using 0.50 $\leq h_{100} \leq$1.0), a number considerably smaller than that called for by Walker et al .

Persic and Salucci (1992) used a Schecter (1976) function which was uncorrected for surface brightness selection effects that effectively limit the volume of space over which LSB galaxies are detected (e.g. Phillipps et al 1993, McGaugh et al 1995b). To rectify this, Impey and Bothun (1997) rederived the baryon density of the universe using a flat number density function (with μ_L = 27.5 mag arcsec^{-2}) and obtained

$$0.014 \leq \Omega_{\rm baryon} \leq 0.025, \qquad (1.2)$$

a number easily within the bounds set by Walker, et al (1991). If the number density is flat, or even increasing with decreasing surface brightness (e.g. Dalcanton et al 1997) it is likely LSB galaxies provide a reasonable solution to the 'missing' baryonic matter problem.

Since this result depends on the space density of galaxies with $\mu_B(0) \geq 24.5$ being as large as those with $\mu_B(0)$ between 23.0 and 24.5 mag arcsec^{-2}we decided to test it as rigorously as we could with our data because our observed distribution is flat only out to $\mu_B(0) =$ 24.0 mag arcsec^{-2}with an apparently strong cutoff at $\mu_B(0) = 25.0$ mag arcsec^{-2}. Our simulations indicate that we have no way of knowing whether or not that cut-off is due to selection effects or to an actual limit on the surface brightness a galaxy can attain in the cluster environment. Although we believe the latter is the case, our simulations in fact show that *no knowledge about the surface brightness distribution of a galaxy population can be determined below the detection limits of the survey.* Thus it is possible, as was proposed in OBC, that we are seeing a true cut-off in the surface brightness distribution of galaxies in clusters, making it likely that the cluster environment prevents the formation of very LSB disk galaxies. On the other hand, our survey has found approximately 120 previously uncatalogued LSB galaxies, increasing the total number of known galaxies in the studied regions by 50%. If yet lower surface brightness disks exist in these regions, it becomes quite clear that this large increase in galaxy number counts would allow LSB galaxies to provide over 50% of the universe's total baryonic density, filling in the entire gap between the predicted baryon density from big bang nucleosynthesis and the observed density from the stellar content of luminous (HSB) galaxies. Resolution of this hypothesis requires still more sensitive and large scale surveys than we have done to date.

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Figure 1. Total colors of the galaxies in this survey (squares) compared to the color of galaxies from numerous other LSB galaxy surveys (Xs). The top two graphs represent U-B versus B-V and V-I versus B-V, respectively. The bottom two graphs show U-B and B-V against central surface brightness ($\mu_B(0)$). The mean values of our data are given by the solid lines, and for the other LSB galaxies by the dashed lines.

Figure 2. Total U-B, B-V and V-I versus central surface brightness ($\mu_B(0)$) (a-c) and U-B versus radius (in arcsec) (d) for the galaxies in this survey. The squares represent galaxies found in the Pegasus region of the sky, Xs represent galaxies found in the Cancer region if the sky, and the triangles represent all the other galaxies. The solid lines are the average values for the Pegasus galaxies, the dashed lines are for the Cancer galaxies, and the dash-dotted lines are for the other galaxies.

Figure 3. Plots of the total color (U-B and V-I) versus inclination for all of the galaxies in our survey. The solid line indicates the average value and the dotted line is the median value for each variable.

Figure 4. Inner 5 arcsec versus outer annulus colors for all of the galaxies in our survey. The solid line is x=y.

Figure 6. Plots of the observed and generated surface brightness distributions for the Monte-Carlo sky simulations. The actual underlying surface brightness is shown in (a), where the solid line is the A (flat) set of simulations and the dashed line is the B (Gaussian) set of simulations. (b) and (c) show the observed distributions for the two distributions and the actual central surface brightness distribution for all the galaxies in this survey (from OBC). The solid line is the observed distributions for the actual Texas data, the dashed line is the observed distributions for the A set (flat underlying surface brightness distribution (Figure 6b)), or the B set (underlying Gaussian distribution (Figure 6c)).

Figure 7. An example of one of the fields with a flat underlying central surface brightness distribution . The white circles indicate galaxies found by the authors, while the black circles indicate galaxies not found by the authors. Parameters for all the galaxies in this image are given in Table 4.

Table 1. The U, B, V, and I colors for all the galaxies in this survey except for those taken 10/26/95-10/30/95. See section 3 for more information.

Table 2. The U, V, and R colors for all the galaxies in this survey taken 10/26/95-10/30/95. See section 3 for more information.

Table 3. The sky brightness (in mag/arcsec^2) through the various filters used in our survey. The values were found by applying our surface photometry techniques to randomly selected areas in each field.

Table 4. Parameters for all the galaxies in Figure 7.

Table 1.

Table 1.

			5”				Total		
Name	m_B	$U-B$	$B-V$	$V-I$	m_B	$U-B$	$B-V$	$V-I$	r_{max}(”)
P1-1	17.83	0.55	0.83	1.21	15.65	0.32	0.82	1.02	48.82
P1-2	19.51	0.43	0.59	1.05	18.27	-0.41	0.72	0.37	15.73
P1-3	18.28	0.67 (± .1)	0.86	0.72	17.15	0.49 (± .1)	0.64	0.70	15.89
P1-4	18.20	1.16	0.93	0.98	16.56	0.27	0.86	1.06	26.79
P1-5	18.93	1.93	1.15	0.92	17.50	0.46	0.89	1.08	15.89
P1-6	18.99	1.73	0.81	1.18	17.92	-0.33	0.86	0.91	15.89
P1-7	18.45	0.98	0.55	1.22	15.14	-0.06	0.90	0.98	52.39
P2-3	18.47	0.32	0.36	0.65	17.42	0.10	0.44	1.10	22.69
P2-1	19.44	0.37	0.52	0.49	18.34	0.19	0.85	0.41	12.23
P2-2	19.81	0.99 (± .2)	0.53	0.12	18.58	0.78	0.86	0.97	15.89
P2-4	22.27	-	1.76 (± 1)	-	17.37	-	0.54(± 1)	-	25.64
P5-1	18.94	0.86	0.74	0.81	17.46	0.11	0.48	0.97	21.54
P5-2	19.06	0.01	0.23	1.26	17.78	0.13	0.68	1.02	15.80
P5-3	19.12	0.68	0.48 (± .2)	1.01	18.05	-0.08	0.66	1.11	14.34
P5-4	19.50	1.21	-0.30	1.98	18.11	-0.16	0.70	1.01	20.00
P5-5	20.96	-0.53	1.62	0.38	18.58	0.47	1.21	0.99	14.18
P5-6	19.54	0.09	0.81 (± .8)	1.03	16.97	0.11	0.72 (± .8)	0.85	34.69
P5-7	18.49	0.83 (± .5)	0.78(± .2)	1.39 (± .2)	16.52	0.34 (± .1)	0.73 (± .1)	0.97 (± .1)	20.58
P6-1	19.55	0.12	1.33	1.43	17.23	0.26	0.94	1.25	30.75
P6-2	18.93	-0.12	0.81	0.75	17.58	-0.17	0.61	0.52	15.00
P6-3	19.65	1.03	0.99	0.37 (± .5)	18.39	-0.09	0.78	0.99 (± .5)	12.90
P6-4	18.57	0.17	0.62	1.07	15.60	0.01	0.67	0.74	55.34
P6-5	19.70	-	1.67	1.34	17.40	-	1.75	1.19 (± .08)	25.31
P6-6	19.64	1.03	0.96	-0.07	18.43	-0.10	0.77	0.97	12.82
P7-1	19.34	0.36 (± .1)	-	1.98†	17.07	-0.03	-	1.91 †	35.71
P9-1	20.78	-1.12	-	2.82†	17.80	-0.20	-	1.80†	17.14
P9-3	20.40	1.45 (± .5)	-	0.80†	18.75	-0.13	-	1.05†	14.75
P9-4	20.84	-0.68	-	2.61†	18.86	-0.16	-	2.57†	17.97
P10-1	20.67	0.26 (± .5)	-	3.19†(± 1)	19.16	0.26	-	3.57†(± 1)	12.15

†No v data. Numbers in the V-I column are actually B-I colors.

Table 1. continued.

	5”				Total				
Name	m_B	$U-B$	$B-V$	$V-I$	m_B	$U-B$	$B-V$	$V-I$	r_{max}(”)
C1-1	18.33	0.24	1.22	1.11	16.75	0.13	1.07	1.20	17.52
C1-2	18.99	1.32	0.97	1.11	18.10	0.66	1.12	1.14	13.39
C1-3	18.10	0.16	0.80	1.07	16.78	0.32	0.91	0.98	13.08
C1-4	18.09	0.74	1.33	0.96	16.55	0.22	1.10	0.97	28.33
C1-5	18.77	0.43	0.98	0.90	16.08	0.06	0.73	0.87	26.48
C1-6	18.18	1.61	0.78	0.79	16.77	0.11	0.88	0.86	24.85
C2-1	18.80	0.21	0.86	0.85	17.65	0.06	0.80	0.96	13.73
C3-1	18.42	0.43	1.03	1.35 (± .06)	17.22	0.03	0.95	1.09 (± .06)	18.47
C3-2	18.17	0.42	0.77	1.34 (± .06)	16.34	-0.05	0.83	1.37 (± .06)	28.94
C3-3‡	19.79	-0.12	0.76	0.083	18.29	-0.05	0.12	1.95	16.80
C3-4	18.55	-0.13	0.94	0.96 (± .06)	17.03	0.06	0.67	0.94 (± .06)	15.14
C3-5	19.34	-0.30	0.93	0.74 (± .06)	17.69	-0.07	0.59	0.82 (± .06)	13.39
C3-6	18.70	-0.14	1.17	0.89 (± .06)	16.41	0.02	0.52	1.01 (± .06)	30.41
C4-1	18.97	-0.10	0.44	-	17.83	-0.10	0.54	-	14.04
C4-2	20.59	-0.63	1.33	-	17.69	-0.31 (± .1)	1.28	-	17.52
C4-3	19.06	-0.41	0.58	-	17.48	-0.18	0.49	-	18.73
C4-4	18.60	0.24	-	-	15.75	-0.16	-	-	33.04
C4-5	18.96	0.16	-	-	18.23	0.96	-	-	11.86
C4-7	20.20	-0.25	0.12	-	19.09	-0.01	0.70	-	12.40
C4-8	19.59	0.23	0.84	-	18.49	0.28	0.76	-	14.28
C5-1	18.48	-0.27	0.69	0.96 (± .06)	17.71	-0.27	0.54	0.91 (± .06)	10.76
C5-2	19.84	0.72 (± .3)	0.77	1.34 (± .06)	18.24	-0.06	0.52	1.54 (± .06)	18.11
C5-3	20.12	-0.71(± .1)	0.40	1.41 (± .1)	18.88	-0.43 (± .2)	1.18	1.33 (± .1)	12.12
C5-4	18.60	0.22	0.96	1.33 (± .06)	17.23	-0.05	0.86	1.33 (± .06)	19.50
C5-5	19.87 (± .2)	0.38 (± .2)	0.40 (± .2)	0.90 (± .2)	18.08 (± .2)	-0.54 (± .2)	0.97 (± .2)	0.92 (± .2)	17.18
C6-1	18.57	-0.02	-	2.35 (± .06)†	17.53	-0.02	-	2.26 †	15.14
C6-5	19.64	-0.44	-	1.79 (± .06) †	18.06	-0.20	-	1.43 †	11.86

†No v data. Numbers in the V-I column are actually B-I colors.

‡The large change between C3-3’s inner (r $\leq$ 5”) colors and total colors is probably due to a star at r=7.9”. Although a mask was placed over the star during the data analysis, light from the star could easily have remained to alter the galaxy’s outer regions, leaving only the inner colors to show C3-3’s true stellar content.

Table 1. continued.

			5”			Total			
Name	m_B	$U-B$	$B-V$	$V-I$	m_B	$U-B$	$B-V$	$V-I$	r_{max}(”)
C6-2	19.14	-0.30	-	1.29 (± .06)†	17.55	-0.20	-	1.59 †	22.36
C6-4	19.33	-0.02	-	1.86 (± .06)†	18.21	0.29	-	1.91 †	18.45
C6-6	19.13	-0.24	-	1.29 (± .06) †	17.80	-0.14	-	1.30 †	14.25
C8-1	19.39	-	0.55	-	18.02	-	0.58	-	16.32
C8-2	18.43	-	-	-	17.57	-	-	-	10.76
C8-3	19.22	-	0.48	-	17.95	-	0.55	-	17.52
C8-4	19.67	-	0.79	-	18.50	-	0.83	-	11.30
C8-5	18.75	-	1.20	-	17.64	-	1.15	-	19.82
C8-6	18.28	-	0.88	-	17.62	-	0.87	-	14.83
C8-8	18.59	-	1.18	-	17.60	-	0.92	-	14.42
C9-1	19.70	0.52	0.68	-0.51	18.15	0.07	0.90	0.15	16.06
C10-1	20.93	-	1.13 (± .07)	0.97 (± .07)	18.88 (± .2)	-	1.33 (± .2)	0.28	14.33
C11-1	18.46	0.95	-	2.22 †	17.75	0.64	-	2.19 †	18.40
C11-3	21.76	-	-	2.77 †	20.01	-	-	2.61 †	10.85
C11-4	18.61	0.93	-	1.24 †	17.20	0.60	-	1.30 †	20.35
C11-5	18.51	0.62	-	2.00 †	17.24	0.60	-	1.73 †	18.00
N1-1	19.13	0.19	-	-	17.62	-0.53	-	-	19.61
N1-2	20.50	-0.75	-	-	18.65	-0.40	-	-	14.96
N1-3	20.19	-0.65 (± .5)	-	-	18.73	-0.73	-	-	12.81
N2-1	19.19	-0.31	-	2.64 (± .06)†	18.32	-0.28	-	2.28 †	11.23
N2-2	18.82	-0.07	-	2.20 (± .06)†	16.99	-0.09	-	2.16 †	28.54
N2-3	18.73	0.45	-	1.23 (± .06)†	18.20	-0.26	-	1.38 †	11.82
N2-4	20.04	-0.17	-	3.02 (± .06)†	18.28	-0.25	-	2.71 †	25.89
N3-1	19.05	-0.02	0.90 (± .1)	-	18.02	0.10	0.58 (± .1)	-	16.29
N3-2	21.59	-	0.76 (± .1)	-	18.63	-	0.35 (± .1)	-	18.77
N3-3	19.56	-0.09	-0.52 (± .1)	-	17.84	-0.56	0.38 (± .1)	-	21.44
N3-4	19.27	0.38	0.27 (± .1)	-	16.49	-0.14	0.44 (± .1)	-	47.43
N7-1	19.90	-0.41	0.86	0.68 (± .06)	18.40	-0.14	0.62	1.10 (± .06)	17.29
N8-1	19.55	1.35	0.82	1.45 (± .06)	18.14	0.17	0.82	1.38 (± .06)	23.48

†No V data. Numbers in the V-I column are actually B-I colors.

Table 1. continued.

	5”				Total				
Name	m_B	$U-B$	$B-V$	$V-I$	m_B	$U-B$	$B-V$	$V-I$	r_{max}(”)
N9-1	18.41	0.29	0.52	-1.29 (± 1)	17.29	0.17	0.61	-0.92 (± 1)	16.90
N9-2	19.80	-	0.32	-1.11 (± .06)	18.89	-	0.82	0.58 (± .06)	12.45
N10-2	18.03	0.62	0.70	1.11 (± .06)	16.57	-0.21	0.82	0.90 (± .06)	26.91
N10-3	19.91	-	0.26	-	18.99	-	0.88	-	12.97
N10-4	19.94	-	0.42	-	18.90	-	0.37	-	10.76
N10-5	21.78	-	-0.16	-	20.54	-	0.27	-	10.76
N11-1	19.16	0.97 (± .5)	1.03	1.12	17.97	0.73 (± .5)	1.05	0.88	14.27
N11-2	18.83	1.02	0.95	1.23	17.70	0.505	1.05	1.248	14.97
U1-1	18.61	-0.15	-	2.06 (± .06)†	17.25	-0.10	-	1.98 †	17.52
U1-2	19.64	-0.03	-	2.31 (± .06)†	18.66	0.02	-	2.26 †	15.41
U1-3	18.33	0.28	-	2.89 (± .06)†	17.66	0.31	-	2.79 †	11.30
U1-4	19.00	0.01	-	1.74 (± .06)†	13.08	-0.05	-	0.87 †	40.93
U1-6	19.84	-0.32	-	0.63 (± .06)†	18.43	-0.86	-	2.02 †	13.07
U1-7	19.30	0.19 (± .1)	-	1.82 (± .06)†	17.69	-0.31 (± .1)	-	2.27†	22.36
U1-8	19.30	0.11	-	2.75 (± .06)†	18.15	-0.24	-	2.50 †	20.68
A1-1	19.23	-0.20 (± .3)	0.74	0.73 (± .06)	17.91	-0.29	0.80	0.62	19.01
A1-2	19.88	-	0.88	-0.37 (± .06)	17.93	-	0.86	1.57	23.41
A1-3	19.71	0.32	1.05	0.85(± .06)	18.43	-0.13	1.24	1.08	14.44
A1-4	18.76	-0.17	1.04	0.71 (± .06)	16.82	-0.09	0.94	0.79	9.760
A1-5	18.92	-0.34	0.87	0.59 (± .06)	17.77	-0.02	0.86	0.69	18.55
I1-1	20.04	0.10	1.010	0.94 (± .06)	14.82	-0.09	0.78	0.92 (± .06)	44.09
I1-2	18.52	0.38	0.72	1.06 (± .06)	16.42	-0.03	0.712	0.81 (± .06)	27.18

†No v data. Numbers in the V-I column are actually B-I colors.

Table 2.

Table 2.

		5”			Total		
Galaxy Ident	m_V	$u - v$	$v - r$	m_V	$u - v$	$v - r$	r_{max}(”)
N4-1	19.58	-0.17 (± .05)	1.16 (± .15)	17.10	0.66	0.49	14.80
N4-2	17.52	2.58 (± .05)	0.67 (± .15)	14.71	0.27	0.76	53.11
N5-1	17.20	-	0.62 (± 0.22)	15.58	-	0.44	14.92
N5-2	16.46	1.88 (± .05)	0.10 (± 0.22)	14.13	0.90	0.09	22.36
N5-3	17.53	0.89 (± .05)	-0.72 (± 0.22)	13.79	0.37	2.18	11.30
N5-4	16.96	0.74 (± .05)	0.24 (± 0.22)	14.98	0.65	0.12	24.66
N6-1	18.67	-	0.46 (± 0.22)	17.70	-	0.74	9.760
N6-2	19.06	-	1.39 (± 0.22)	14.50	-	2.50	21.30
N6-3	17.29	1.73 (± .05)	0.56 (± 0.22)	15.47	0.92	0.67	22.52
N6-4	18.61	-	0.51 (± 0.22)	15.97	-	0.44	29.97

Table 3. The sky brightness (in mag/arcsec^2) through the various filters used in our survey. The values were found by applying our surface photometry techniques to randomly selected areas in each field.

Filter	**Average (mag/arcsec^2)**	**Standard Deviation**	**Range**
B	21.75	± .26	$21.21 \leq \mu_B \leq 22.44$
U	21.07	± .31	$20.50 \leq \mu_U \leq 21.79$
V	20.67	± .30	$19.97 \leq \mu_V \leq 21.92$
I	18.54	± .51	$18.04 \leq \mu_I \leq 21.72$
R	19.34	± .15	$19.04 \leq \mu_R \leq 21.66$

Table 4. Parameters for all the galaxies in Figure 7.

μ_0 **(mag arcsec^{-2})**	α **(")**	**Bright Core?**	**found?**
22.15	1.7	y	y
27.09	18.1	n	n
23.04	4.7	n	y
27.34	1.1	y	n
26.58	1.2	n	n
25.38	4.8	y	n
22.29	0.9	y	n
22.64	7.3	y	y
26.09	4.1	y	n
26.17	5.8	y	n
25.17	7.2	y	y
21.90	7.9	y	y
25.40	8.4	n	y
27.92	3.5	y	n
22.61	4.2	y	y
23.15	5.1	y	y
26.07	3.4	y	n
21.65	5.3	n	y
23.47	5.5	y	y

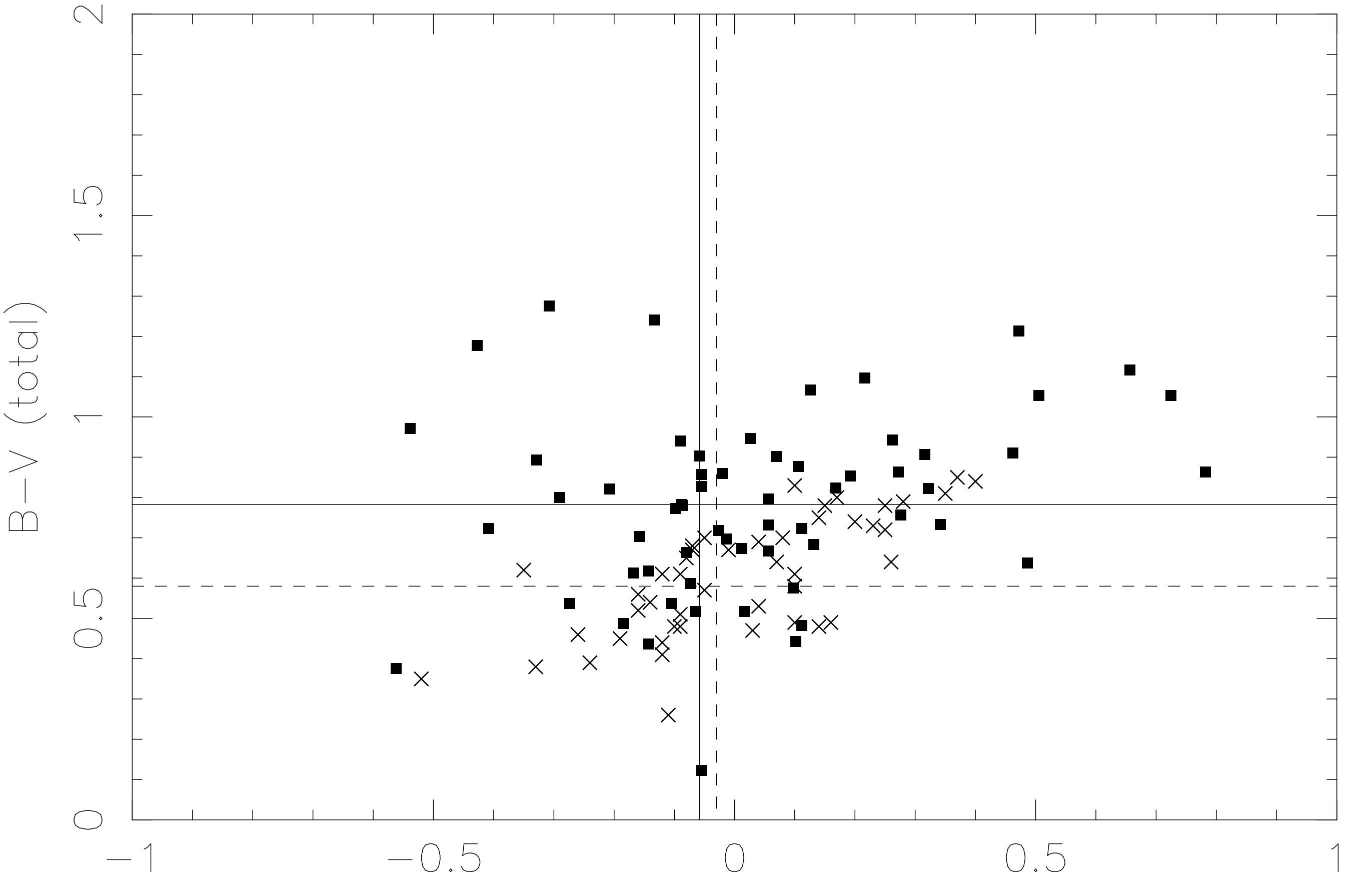

Figure 1. a

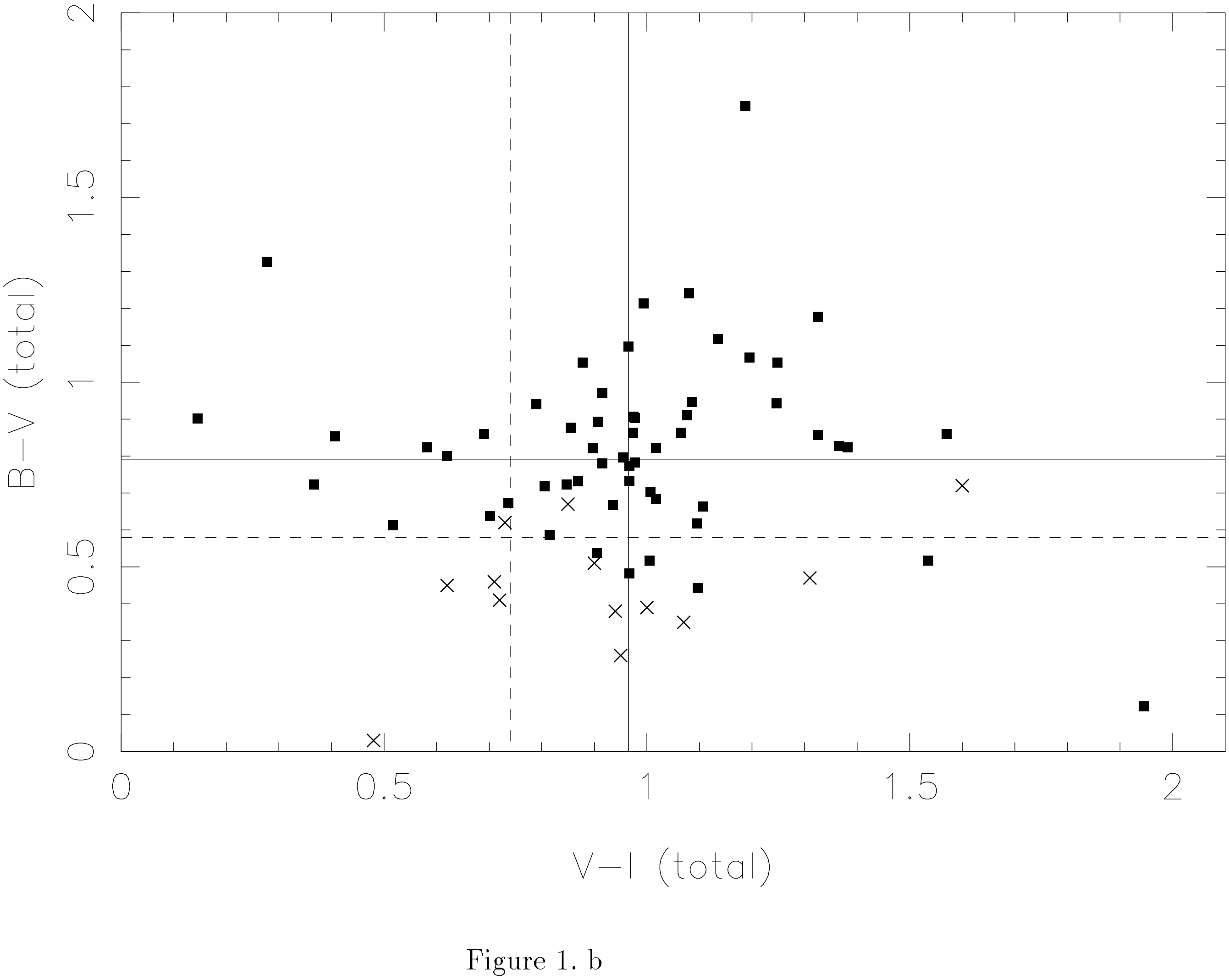

Figure 1. b

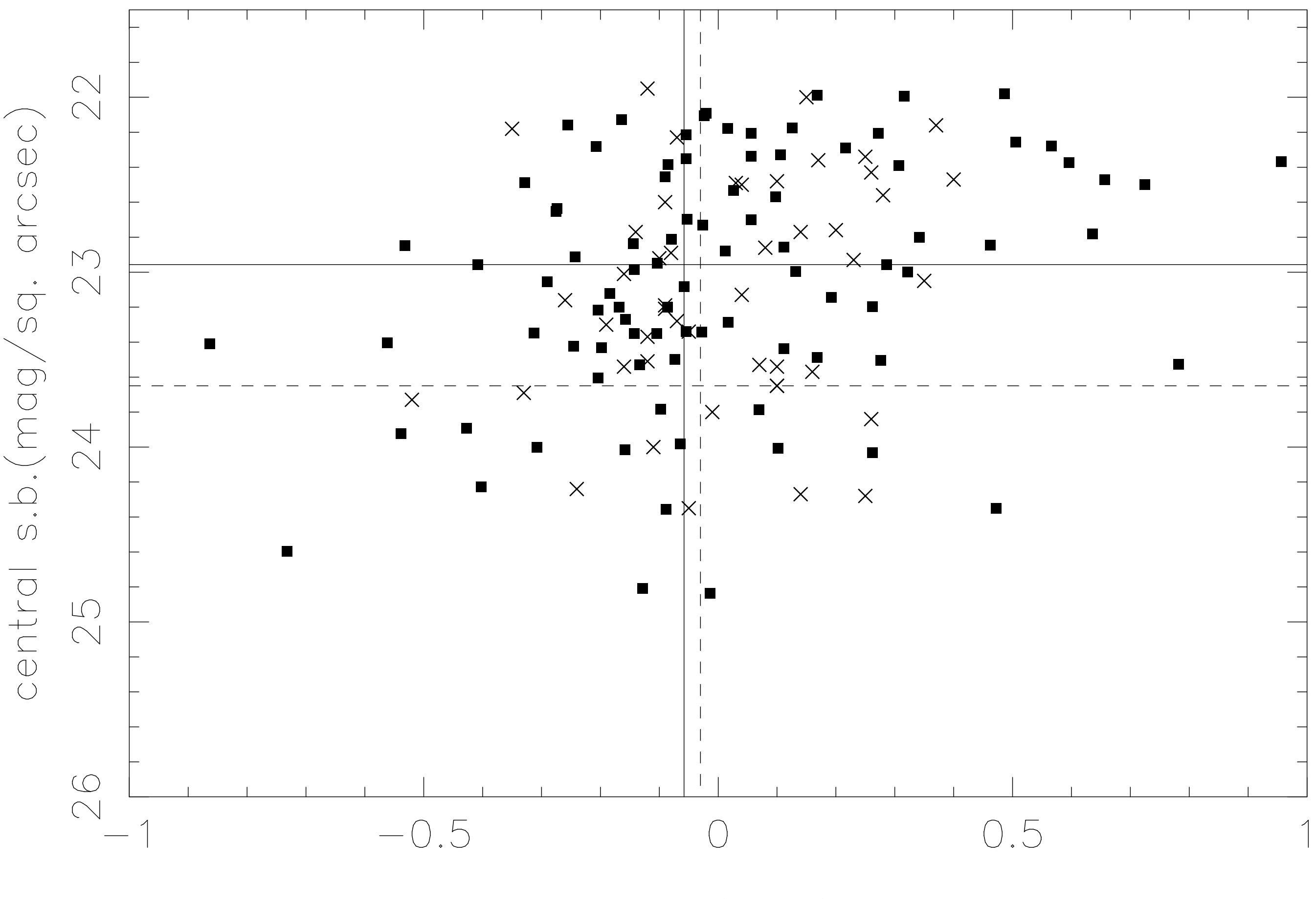

Figure 1. c

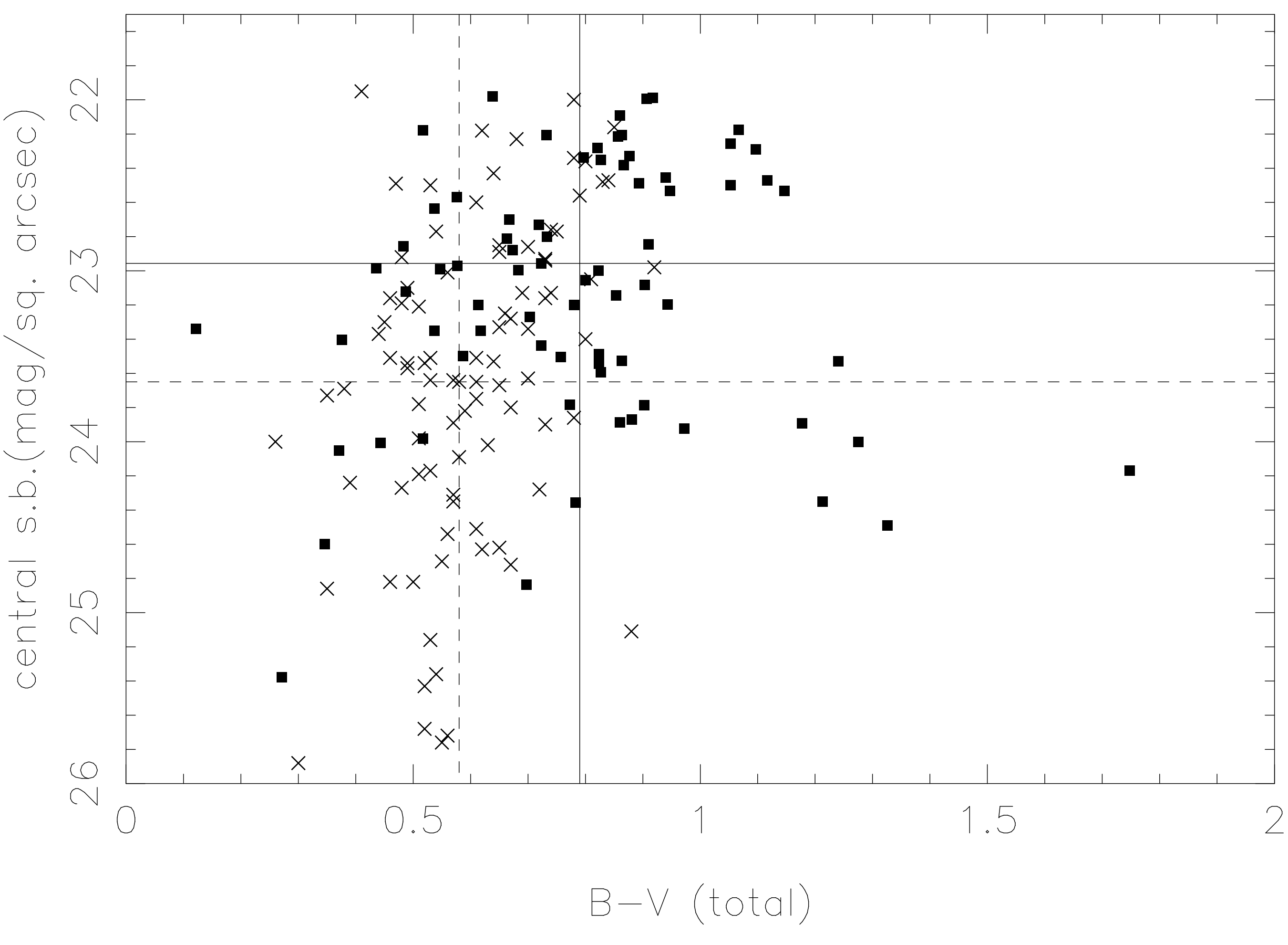

Figure 1. d

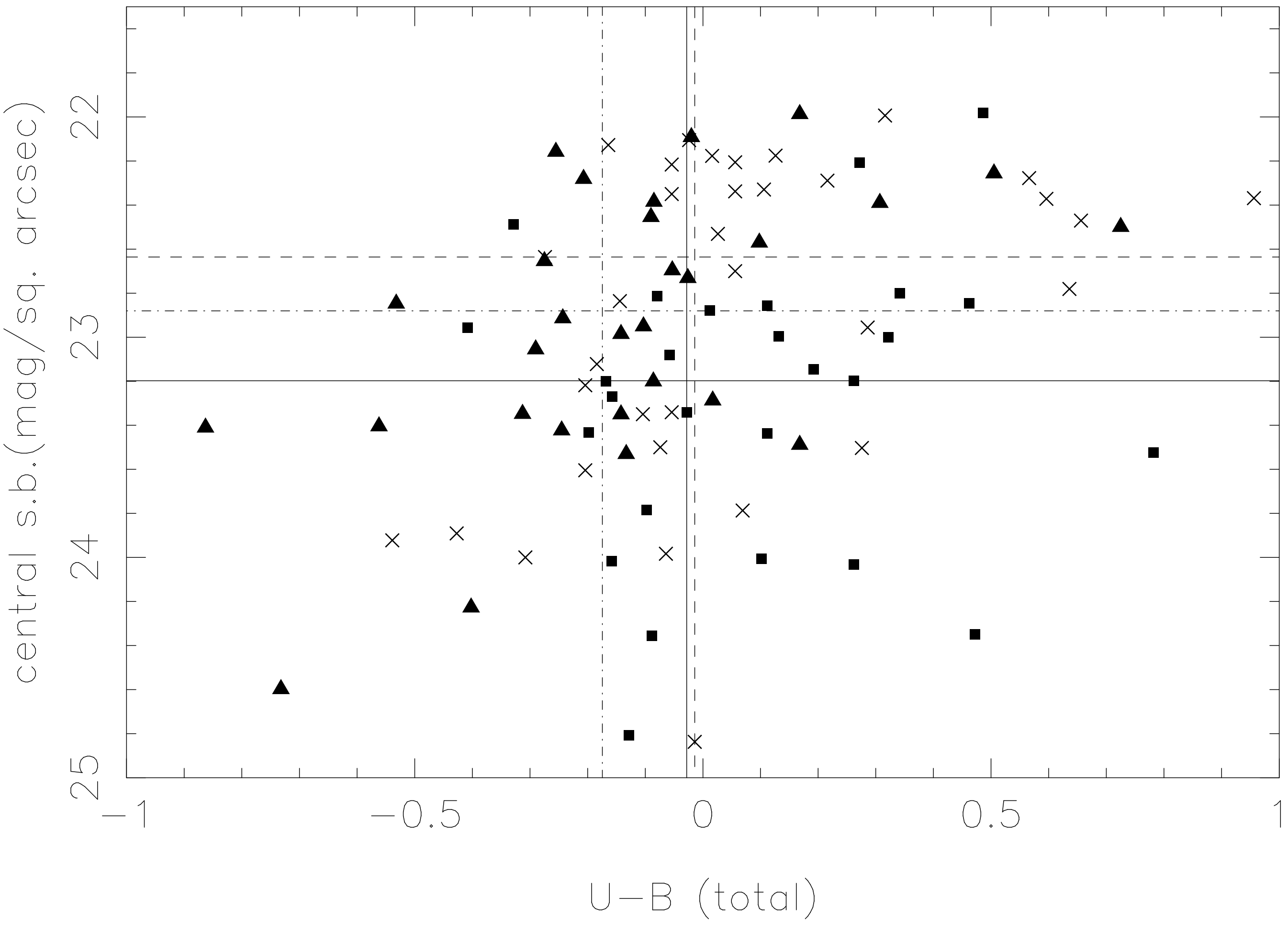

Figure 2. a

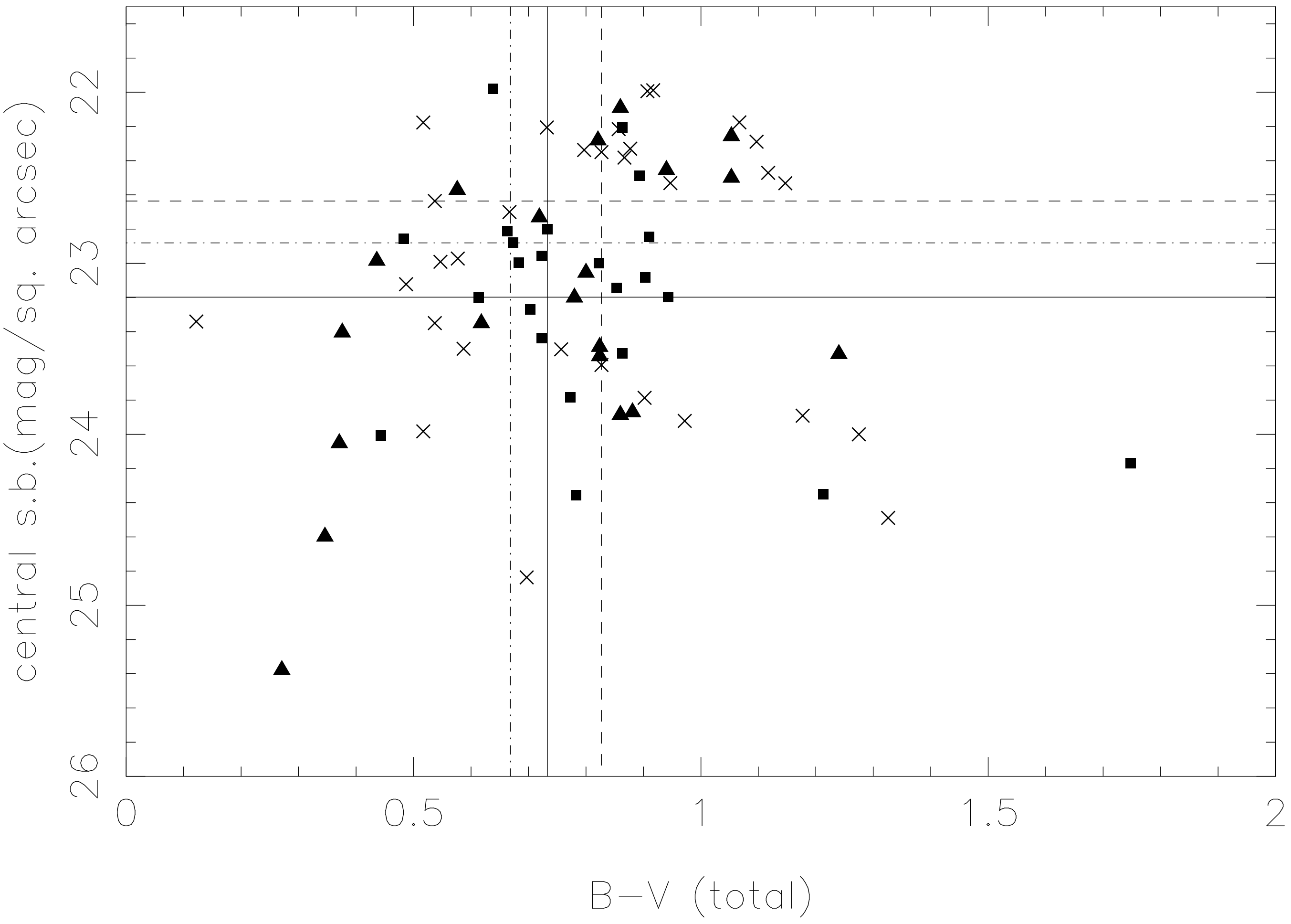

Figure 2. b

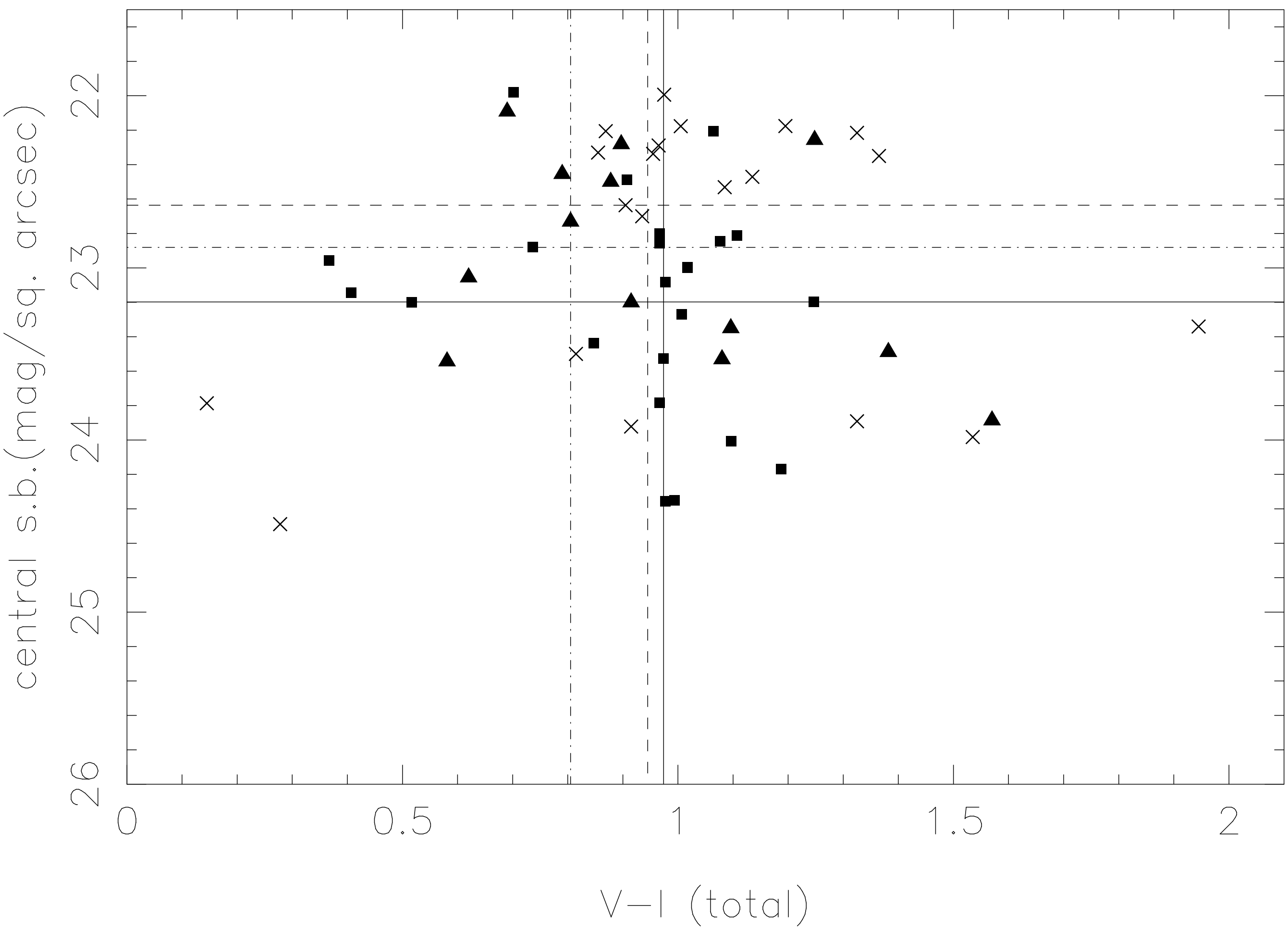

Figure 2. c

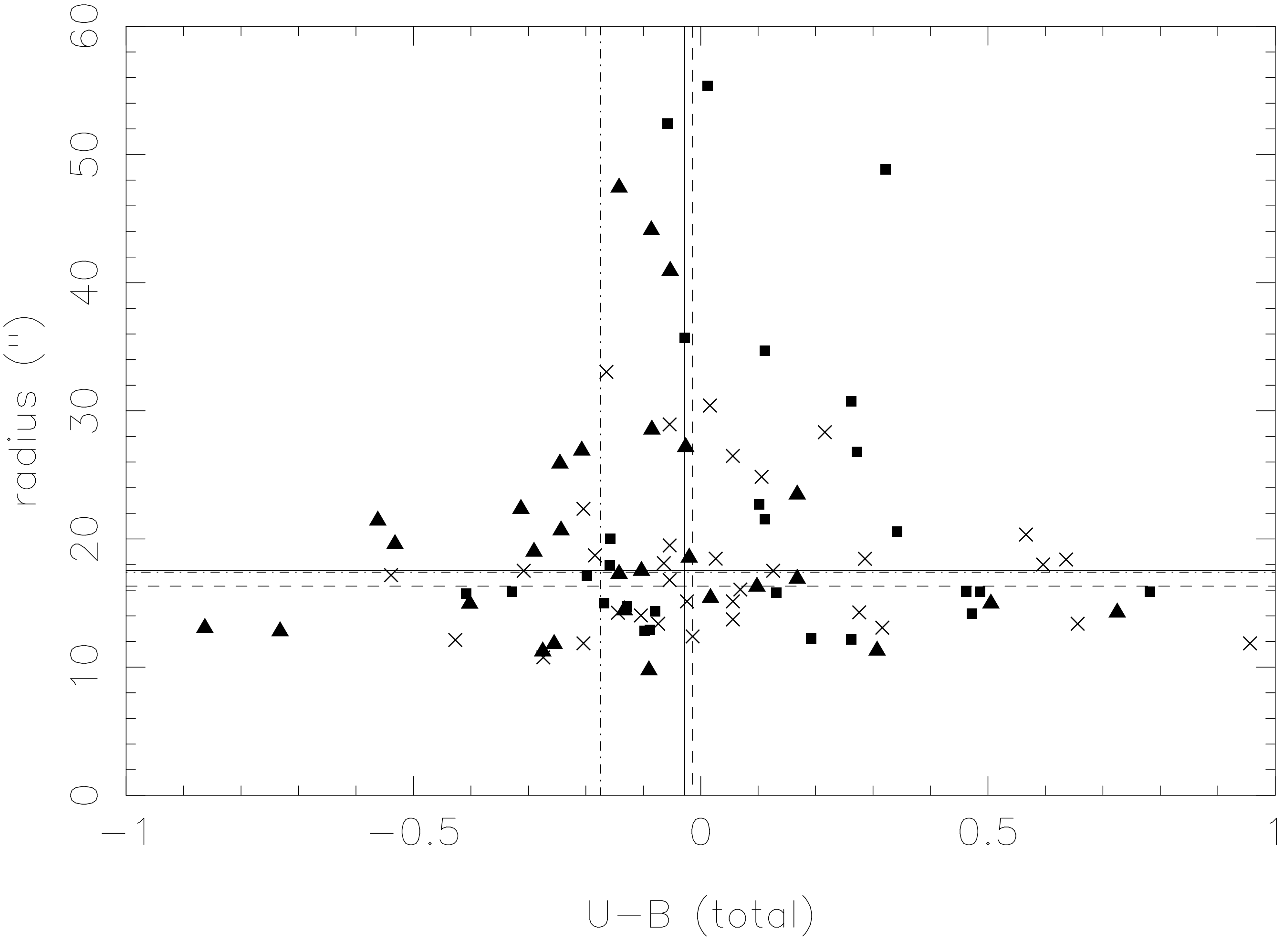

Figure 2. d

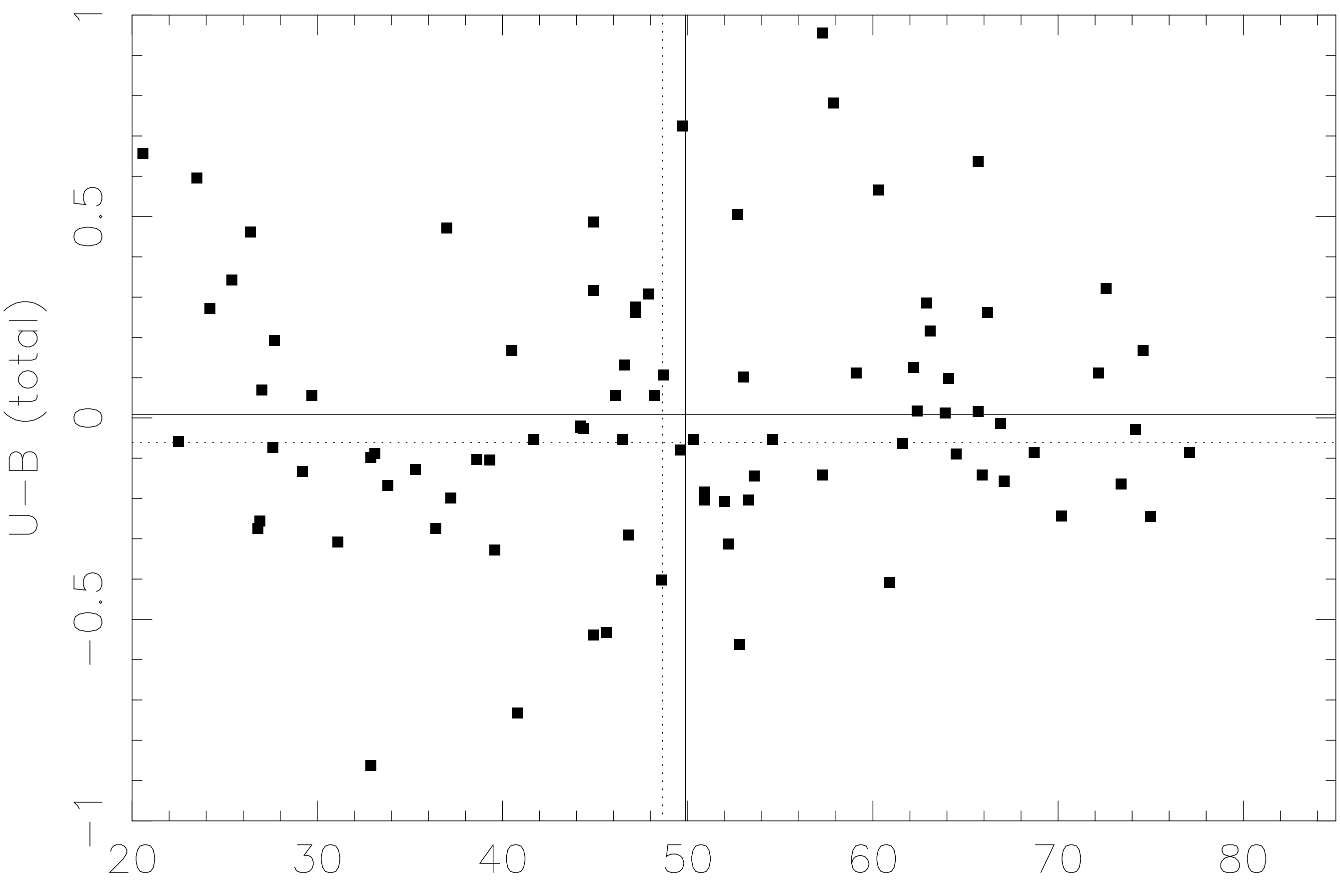

Figure 3. a

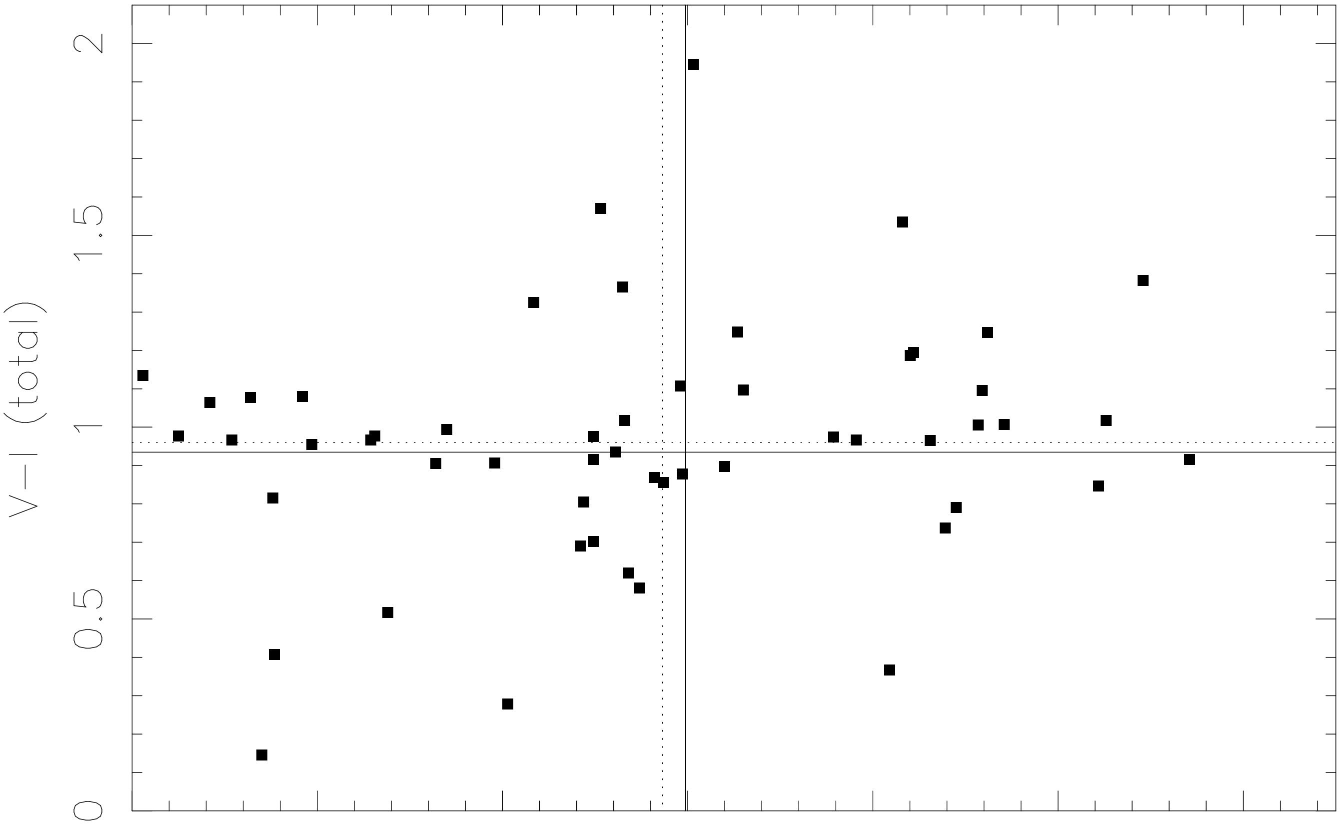

Figure 3. b

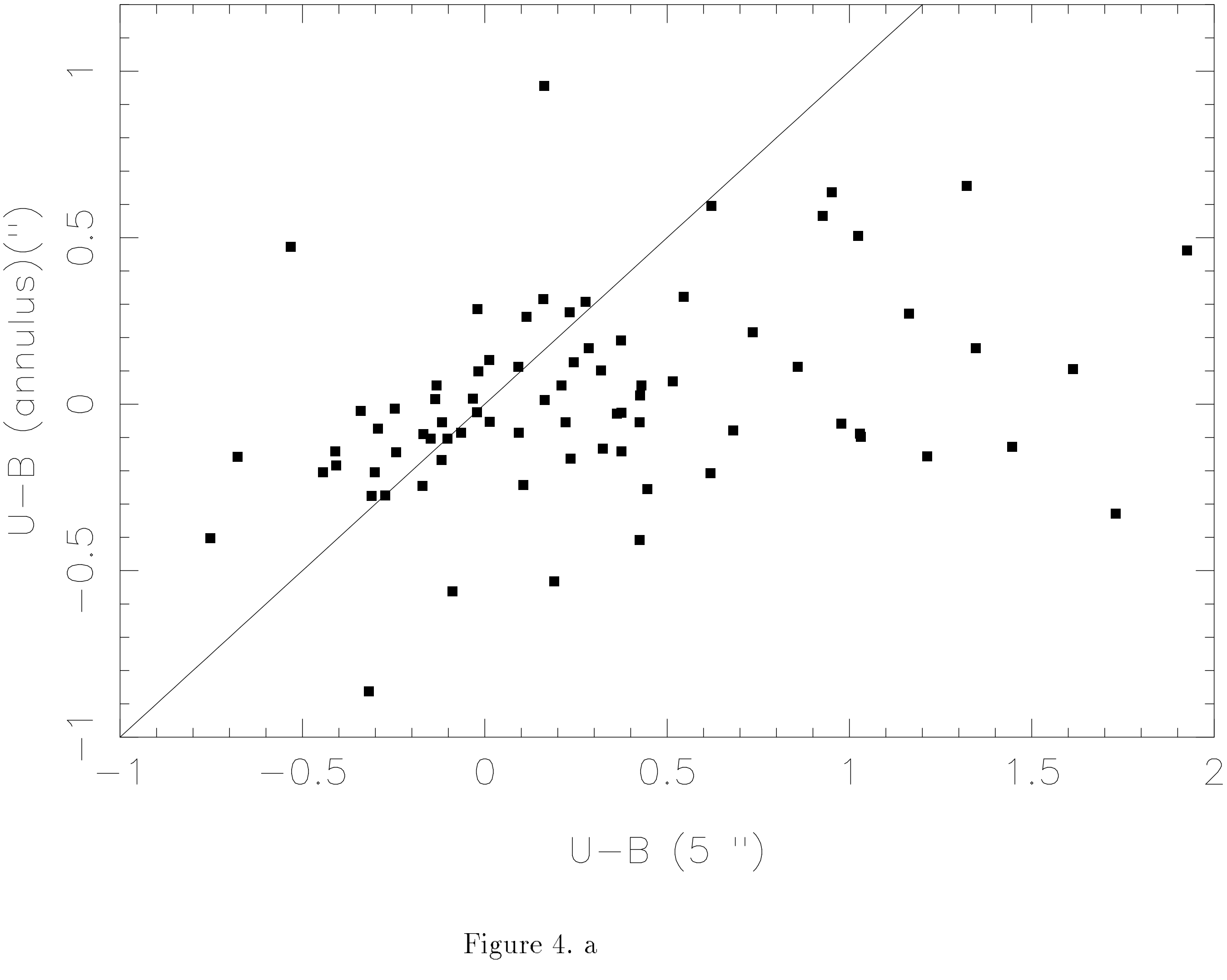

Figure 4. a

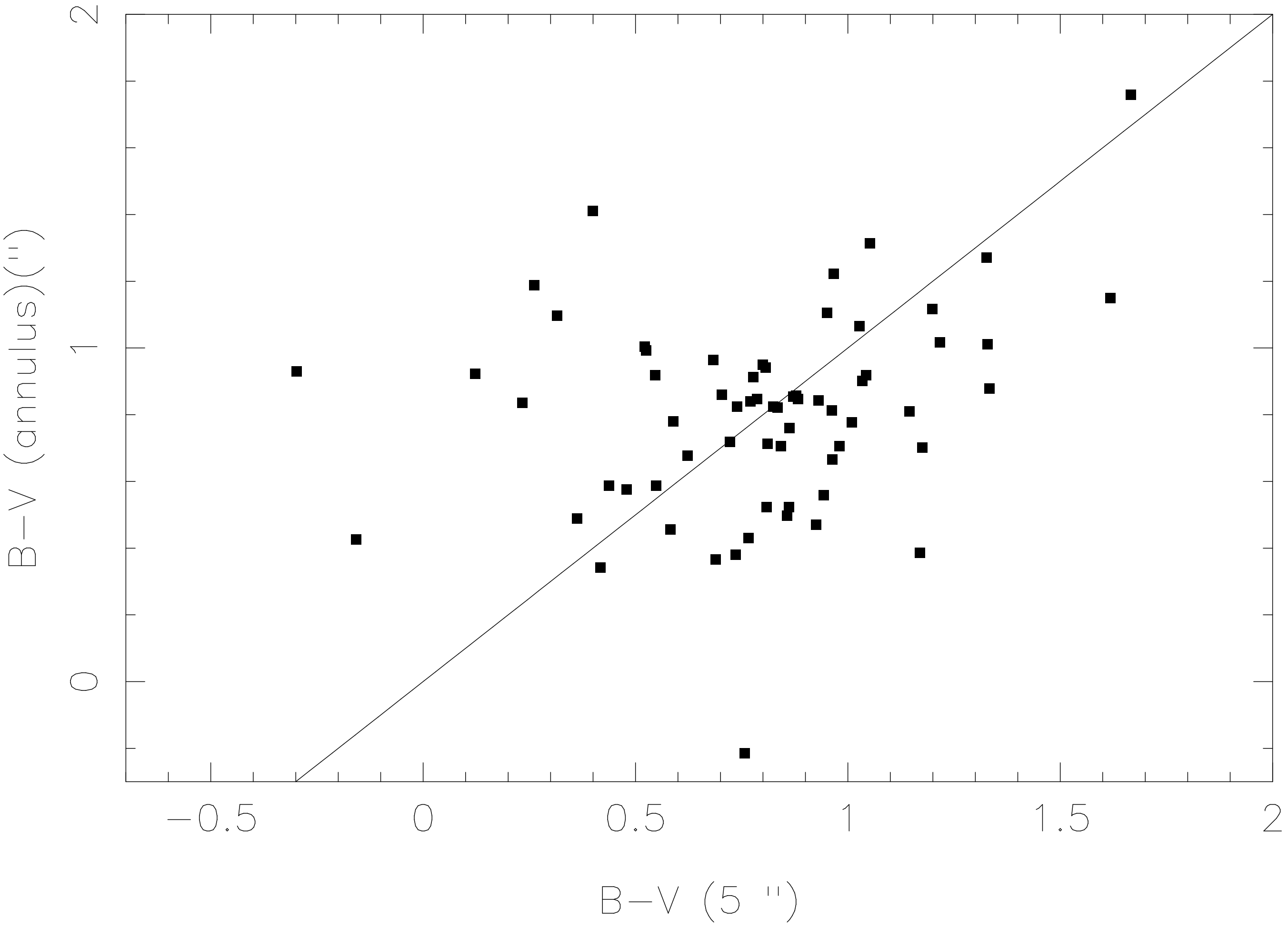

Figure 4. b

Figure 4. c

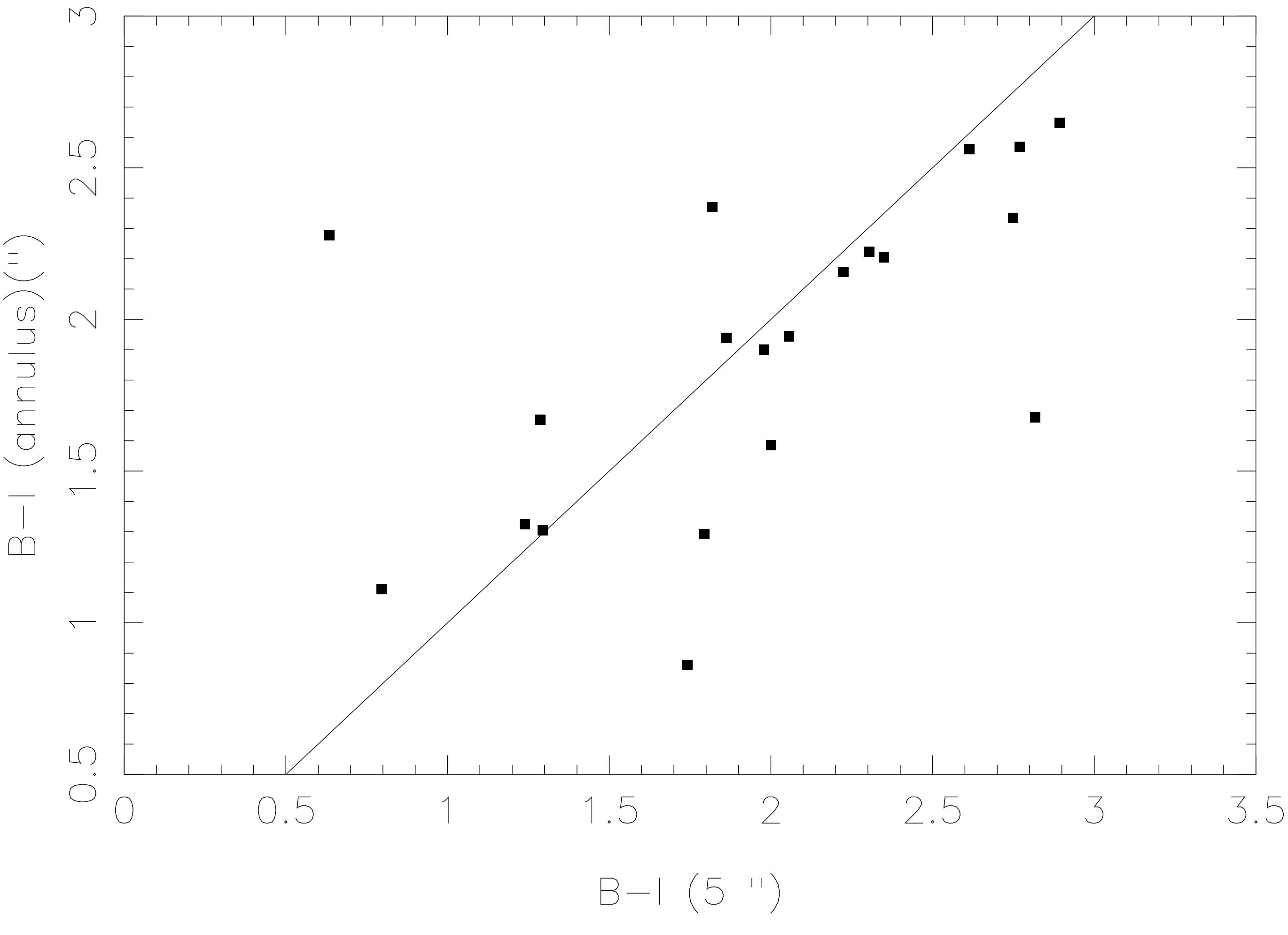

Figure 4. d

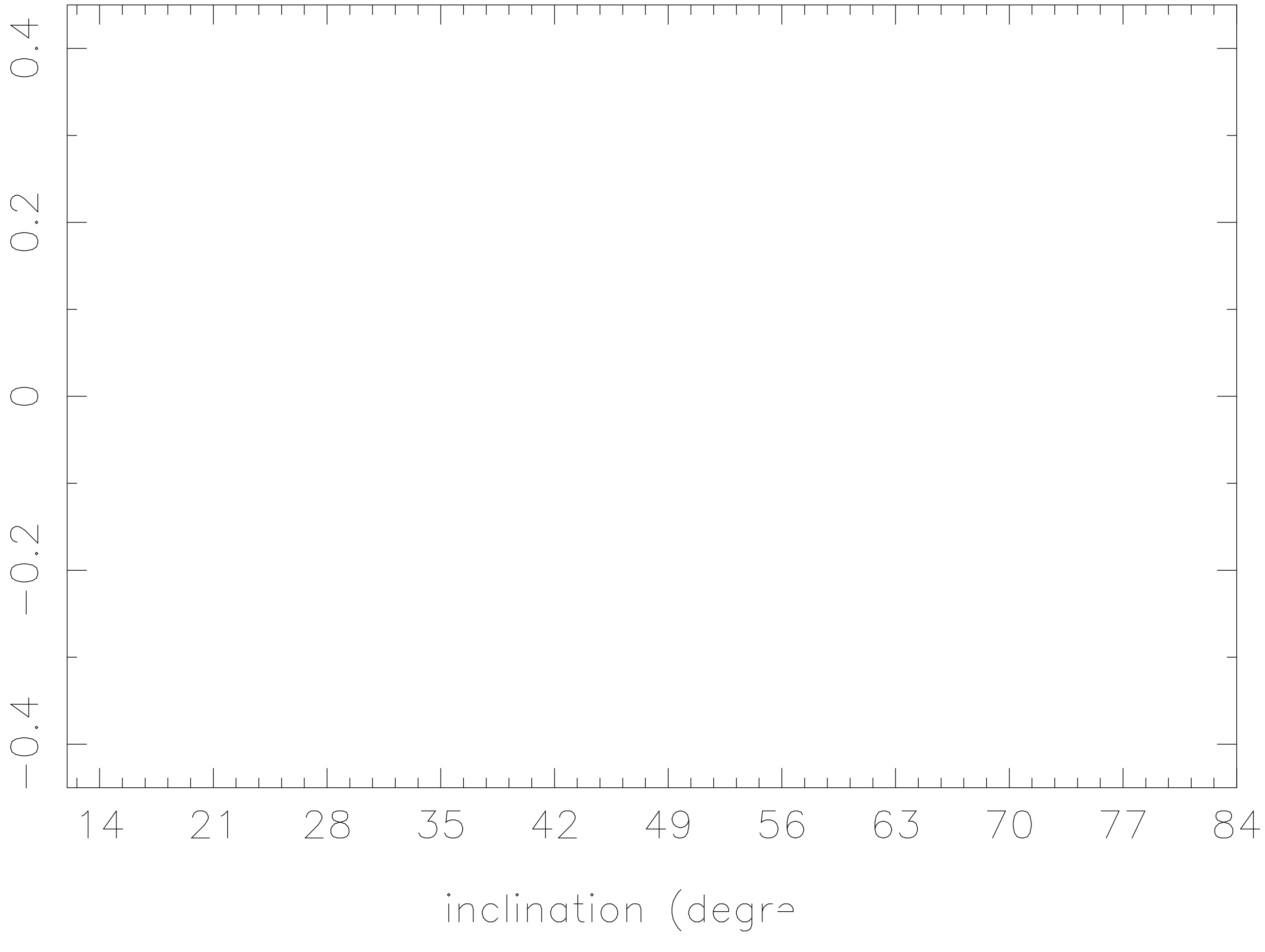

Figure 5. a

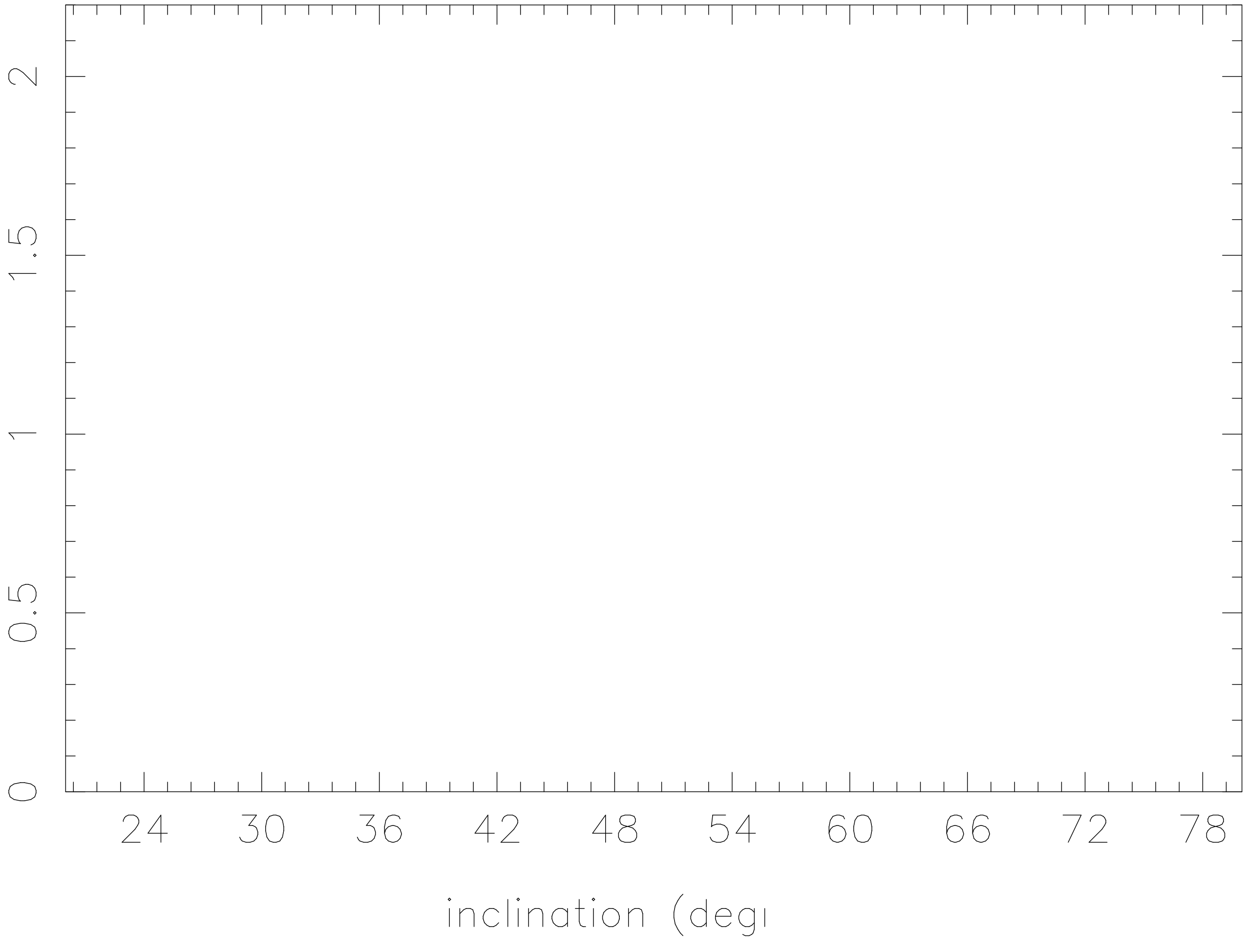

Figure 5. b

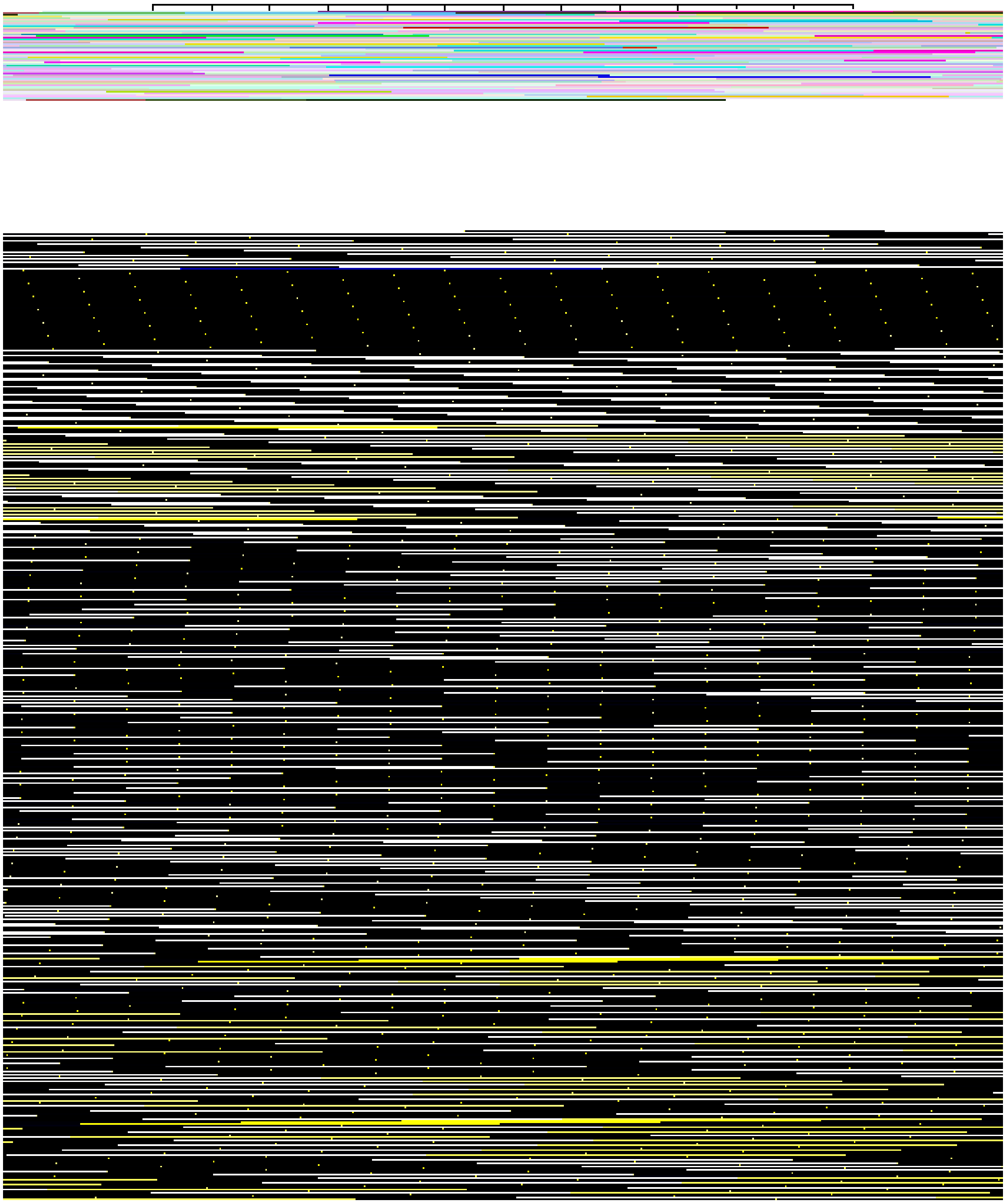

Figure 6. b

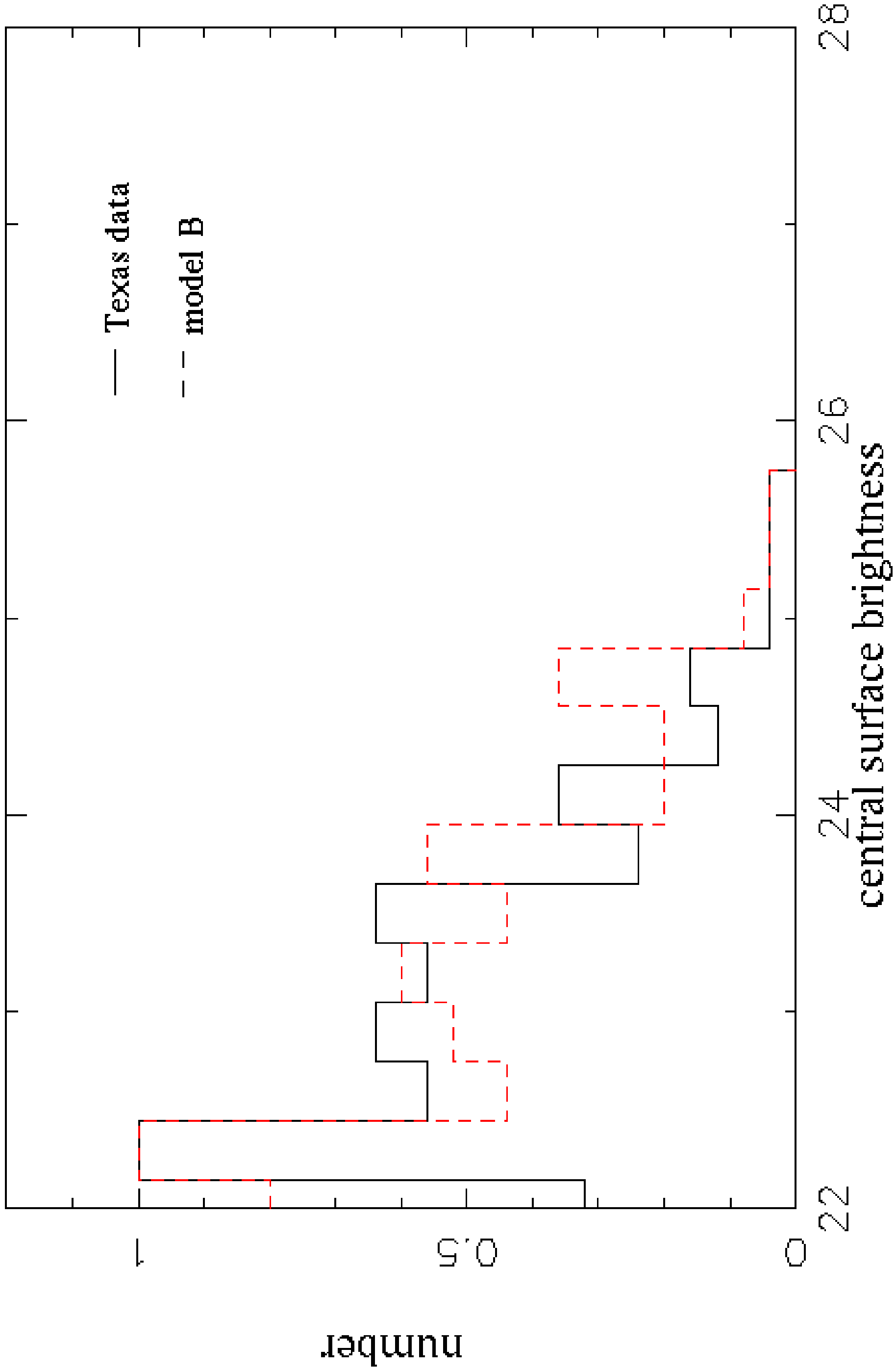
Texas data
model B
central surface brightness
number
22
24
26
28
0
0.5
1

Figure 6. c

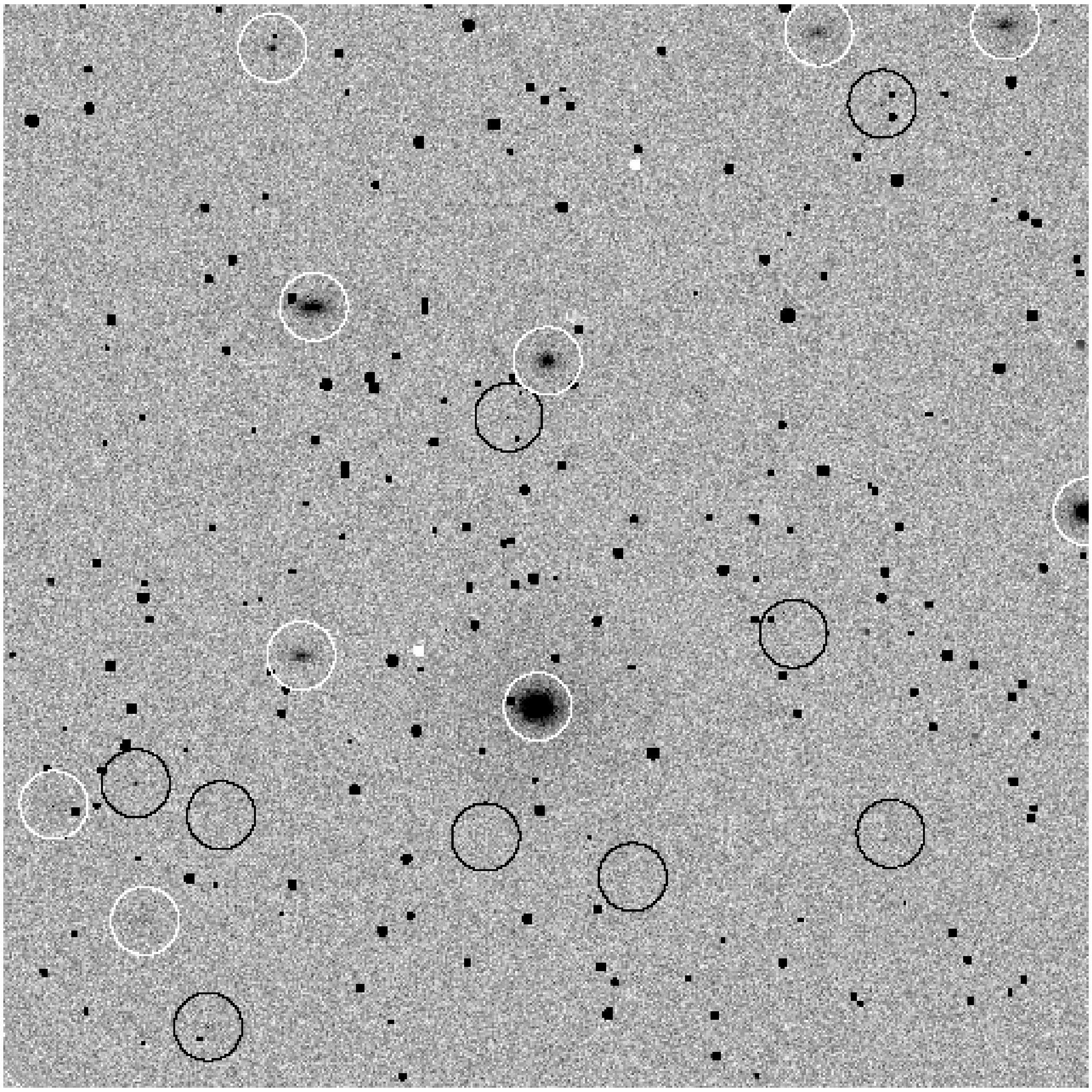

Figure 7.