ULTRAVIOLET-OPTICAL PIXEL MAPS OF FACE-ON SPIRAL GALAXIES: CLUES FOR DYNAMICS AND STAR FORMATION HISTORIES

PAUL B. ESKRIDGE, JAY A. FROGEL, VIOLET A. TAYLOR, ROGER A. WINDHORST, STEPHEN C. ODEWAHN, CLAUDIA A. T. C. CHIARENZA, CHRISTOPHER J. CONSELICE, RICHARD DE GRIJS, LYNN D. MATTHEWS, ROBERT W. O’CONNELL, AND JOHN S. GALLAGHER III

ABSTRACT

Ultraviolet and optical images of the face-on spiral galaxies NGC 6753 and NGC 6782 reveal regions of strong ongoing star formation that are associated with structures traced by the old stellar populations. We use these images to construct NUV-(NUV−I) pixel color-magnitude diagrams (pCMDs) that reveal plumes of pixels with strongly varying near-ultraviolet (NUV) surface brightness and nearly constant I surface brightness. The plumes correspond to sharply bounded radial ranges, with (NUV−I) at a given NUV surface brightness being bluer at larger radii. The plumes are parallel to both the reddening vector and simple model mixtures of young and old populations, thus neither reddening nor the fraction of the young population can produce the observed separation between the plumes. The images and radial surface brightness and color plots indicate that the separate plumes are caused by sharp declines in the surface densities of the old populations at radii corresponding to disk resonances. The maximum surface brightness of the NUV light remains essentially constant with radius, while the maximum I surface brightness declines sharply with radius. A mid-ultraviolet (MUV) image of NGC 6782 shows emission from the nuclear ring. The distribution of points in an (MUV−NUV)-(NUV−I) pixel color-color diagram is broadly consistent with the simple mixture model but shows a residual trend that the bluest pixels in (MUV−NUV) are the reddest pixels in (NUV−I). This may be due to a combination of red continuum from late-type supergiants and [S ii] emission lines associated with H ii regions in active star-forming regions. We have shown that pixel mapping is a powerful tool for studying the distribution and strength of ongoing star formation in galaxies. Deep, multicolor imaging can extend this to studies of extinction and the ages and metallicities of composite stellar populations in nearby galaxies.

Subject headings: galaxies: individual (NGC 6753, NGC 6782) — galaxies: photometry — galaxies: spiral — galaxies: structure — ultraviolet: galaxies

1. INTRODUCTION

It has been known since the 1950s that spiral galaxy morphology can be a strong function of wavelength (Zwicky 1955). Different bandpasses transmit differing amounts of light from young versus old stellar populations and are affected by dust extinction in different ways. Classical galaxy morphology is based on blue-sensitive photographic data and is thus strongly influenced by the distribution of recent star formation and dust. Over the last two decades it has become increasingly clear that the underlying distribution of the old stellar mass, as traced by red or near-infrared (NIR) imaging, can be quite different than the B-band morphology (e.g., Hackwell & Schweizer 1983; Block et al. 1994; Frogel, Quillen, & Pogge 1996; Eskridge et al. 2002). The ability to image galaxies in the vacuum ultraviolet increases the lever arm over which we can study the wavelength dependence of galaxy morphology and can allow us to draw a sharp distinction between UV-bright regions and the NIR luminosity distribution. In the B band, even actively star-forming galaxies have a significant contribution to their flux from stars as old as a few gigayears (e.g., Sage & Solomon 1989). By contrast, in the vacuum ultraviolet nearby late-type galaxies are dominated by regions of current unobscured active star formation. The spiral arms are prominent, as are star-forming rings (if present), and the bulges are weak or not visible at all (e.g., Kuchinski et al. 2000, 2001; Marcum et al. 2001; Windhorst et al. 2002). The distribution of current, unobscured, active star formation in a galaxy, provided by the ultraviolet morphology, offers us a map of the dynamically interesting places in the disk. The distribution of the old stars, from red or NIR imaging, tells us about the underlying gravitational potential.

One means of examining multicolor imaging data of unresolved sources is to examine the properties of the image
stack on a pixel-by-pixel basis. This approach has recently been advocated by Abraham et al. (1999) but was first discussed by Bothun (1986). Abraham et al. (1999) made pixel color-color diagrams and found relationships between location in these color-color diagrams and physical location within the target galaxy. They used Hubble Space Telescope (HST) images of faint intermediate-redshift galaxies in the Hubble Deep Field, taken with the Wide Field Planetary Camera 2 (WFPC2). In this paper we bring the technique back to $z = 0$ and apply it to the study of star formation in nearby spirals.

Our data include moderately deep HST/WFPC2 exposures for the spiral galaxies NGC 6753 and NGC 6782 in two bandpasses (F300W or near-ultraviolet [NUV], and F814W or $I_{614}$). We also have a shallow F255W (or mid-ultraviolet [MUV]) image of NGC 6782. As we have moderately deep images in only two bandpasses, we adopt the approach of Bothun (1986), who first made a pixel color-magnitude diagram (pCMD) for NGC 4449. The advantages we have over Bothun’s earlier work derive from the special attributes of the HST/WFPC2 combination. As HST is in orbit, we can take data in the vacuum ultraviolet as well as the red part of the optical bandpass. This gives us a larger spectral baseline to work with. The other, somewhat paradoxical advantage is that WFC images are undersampled. This has the consequence that individual pixels are statistically independent. Thus, well-aligned multiband images with WFPC2 provide a set of statistically independent pixels, each of which contains information on the stars within it. Each pixel contains a mix of different stellar populations, dust and gas, and can be treated as a distinct physical unit, similar in some ways to the study of star clusters. The number and bandpasses of the available images determine the sorts of information a given data set will probe. The combination of NUV and $I_{614}$ images we have available is primarily sensitive to the relative fractions of young and old stellar populations.

Traditional studies of the structure and contents of galactic disks are based on radial, azimuthally averaged, color and surface brightness profiles (e.g., Kormendy 1977; Kent 1985; Walterbos & Kennicutt 1987; de Jong 1996; Baggett, Baggett, & Anderson 1998; de Grijs 1998; Peng et al. 2002). This washes out any small-scale effects (due, for instance, to spiral arms and interarm regions). We combine these more traditional approaches with the pixel-mapping technique to gain a fuller picture of the distribution of stellar populations in the disks of spirals.

Our targets for this study are both bright, nearly face-on early- to mid-type spiral galaxies. Because of their small angular size (they fit well within the WFPC2 field of view), they are the only two galaxies from the Ohio State University Bright Spiral Galaxy Survey sample (Eskridge et al. 2002) to have been included in the HST UV imaging sample of Windhorst et al. (2002). Both galaxies were previously known to be UV sources (Bowyer et al. 1995). The basic properties of the target galaxies are given in Table 1. In § 2 we describe the observations in detail, discuss steps we have taken to address the red leak of the UV filters, and present our adopted photometric calibration. We present the NUV-(NUV−$I_{614}$) pCMDs for both galaxies in § 3. We consider and correct for the effects of red leak. One of our technical justifications for obtaining images with the F814W filter was to allow for good red-leak correction to the NUV images; the bandpass of the F814W filter is very similar to that of the F300W red leak (see Windhorst et al. 2002).

As both NGC 6753 and NGC 6782 are early-type spirals, they are likely to be brighter in the wavelength regime of the red leak than they are in the NUV. One can make a very simple worst-case estimate of the red leak as follows: The red leak cannot account for any more than all of the counts in any given area of a few pixels of an NUV image. One can

| Parameter | NGC 6753 | NGC 6782 | References |
|-----------|----------|----------|------------|
| Classification | (R)SA(r)b | (R)Sab(r)a | 1 |
| $\alpha$ (J2000.0) | 19 11 23.4 | 19 23 57.2 | 1 |
| $\beta$ (J2000.0) | −57 02 56 | −59 55 22 | 1 |
| $m_B$ | 11.83 | 11.84 | 1 |
| $V_c$ (km s$^{-1}$) | 3142 | 3736 | 1 |
| $D$ (Mpc) | 42.6 | 51.2 | 1.2 |
| $M_B$ | −21.3 | −21.7 | 1.2 |
| $(B-V)$ | 0.83 | 0.92 | 1 |
| $D_{25}$ (arcmin) | 2.5 | 2.2 | 1 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

References.—(1) de Vaucouleurs et al. 1991. (2) Distance derived using the Yahil, Tammann, & Sandage 1977 formalism and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. OBSERVATIONS AND DATA REDUCTION

The data for this study are a set of UV and optical images obtained with the WFPC2 on board HST. For both NGC 6753 and NGC 6782, we have HST WFPC2 images taken through the F300W and F814W filters. For NGC 6782 we also have an image obtained through the F255W filter. Details of the observations are given in Table 2.

The nuclei of the target galaxies were placed on the WF3 chip. In Figure 1 we show $50'' \times 50''$ sections of the WF3 images, centered on the galaxy nuclei. These data were obtained as part of the HST program 8645, “A Survey of Mid-UV Morphology of Nearby Galaxies: Galaxy Structure and Faint Galaxy Evolution” (PI: R. Windhorst). Details of the program and data reduction are given in Windhorst et al. (2002).

2.1. Red-Leak Correction

The F300W filter has significant secondary throughput from $\sim 6600$ Å to $\sim 1$ μm. Thus, if one wishes to do good quantitative work with WFPC2 F300W images, one must consider and correct for the effects of red leak. One of our technical justifications for obtaining images with the F814W filter was to allow for good red-leak correction to the NUV images; the bandpass of the F814W filter is very similar to that of the F300W red leak (see Windhorst et al. 2002).

As both NGC 6753 and NGC 6782 are early-type spirals, they are likely to be brighter in the wavelength regime of the red leak than they are in the NUV. One can make a very simple worst-case estimate of the red leak as follows: The red leak cannot account for any more than all of the counts in any given area of a few pixels of an NUV image. One can

| Image | Date | Exposure (s) | Date | Exposure (s) |
|-------|------|-------------|------|-------------|
| NUV   | 2000 Jun 22 | 2 × 950 | 2000 Jun 22 | 3 × 467 |
| $I_{614}$ | 2000 Jun 22 | 2 × 160 | 2000 Jun 22 | 2 × 130 |
therefore take the $I_{814}$ image and iteratively scale it until one finds a maximum possible red-leak contamination on these grounds (that is when all of the counts in any region of the NUV image are actually due to red leak). We note that this is almost certainly an overestimate of the red leak, as the old stars that dominate the emission in the $I_{814}$ image will also emit some NUV photons. But even in this most extreme case, there is no substantial qualitative difference between the uncorrected and corrected NUV frames for our targets. To understand why this is so, note in Figure 1 that the light profiles of both galaxies are strongly peaked in the $I_{814}$ band but only weakly peaked in the NUV. Thus, when the $I_{814}$-band images are scaled with the constraint that the subtracted image has no significant negative regions, this has the effect that the subtracted images reach zero counts in the dust lanes around the nuclei, while the nuclei themselves and the surrounding regions of star formation are nearly unaffected.

One can attempt a more accurate assessment of the red leak in a number of ways. One relatively simple method is to...
fold model galaxy spectra through the response functions of the HST/WFPC2+F814W and F300W combinations and measure the expected red leak for various input spectra. We undertook this experiment using spectral models from the Bruzual & Charlot (1993) atlas, as implemented in the SYNPHOT package (Bushouse & Simon 1998) within STSDAS.12 We proceeded as follows: For our two targets, we used the Bruzual & Charlot (1993) models to derive the observed NUV count rate in the same aperture, row 3 shows the red leak NUV count rate for the model, and row 4 shows the fraction of the observed counts in the aperture that are due to red leak.

We have also made empirical red-leak corrections, using template spectra from the Kinney atlas (Kinney et al. 1996). We used their Sa (for NGC 6782) and Sb (for NGC 6753) template spectra. Our procedure for the Kinney atlas templates is the same as outlined above for the model templates, and the results are included in Table 3. Both the Bruzual & Charlot (1993) model spectra and the Kinney et al. (1996) templates give consistent results. The F300W red leak does not have any qualitative effect on the NUV morphology of our target galaxies. Even in the nuclei, the red leak accounts for less than 10% of the counts in the NUV images of either galaxy. Further, the range in red-leak correction factors for all the templates considered is only a fraction of a percent in both galaxies. We conclude that the F300W red leak does not have any qualitative effect on the NUV morphology.

For the F255W image of NGC 6782, we make no attempt at red-leak correction. First, the F255W red leak is at ~4000 Å, and we have no HST images at this wavelength. Second, the total counts in a 20 pixel radius aperture, centered on the nucleus, are consistent with 0. Thus, there simply is no room in the data for a significant red leak. We note that the WFPC2 Handbook (Biretta et al. 2000) also shows that the F255W red leak is also significantly smaller than the F300W red leak.

### 2.2. Photometric Calibration

We adopt the photometric calibration from the STScI documents archive,13 dated 1998 July 1. The adopted WF3 gain 7 zero points are given in Table 4. To compute magnitudes from a given count rate, we adopt the relation

$$m = ZP - 2.5 \log \left( \frac{DN}{t_{\text{exp}}} \right)$$

where DN is the total counts, $t_{\text{exp}}$ is the exposure time, and ZP is the zero point for the filter. These calibrations are based on those given by Holtzman et al. (1995), with corrections due to the aging of the detectors. Our photometry is thus on the Vegamag system.

The basic reduction of the data in this paper is described in detail in Windhorst et al. (2002). An issue that requires further attention for this study is sky subtraction. We measured the sky levels in the original images after the STSDAS "on-the-fly" pipeline calibration, but before cosmic-ray clipping (the cosmic-ray clipping routine must add small constants to each image to bring all images onto one common sky). Table 4 gives our measured sky level in each band in units of mag arcsec$^{-2}$.

### 3. UV-OPTICAL PIXEL CMD

We use a pixel-mapping technique (Bothun 1986; Abraham et al. 1999) to examine the data. As we have only two moderately deep images per galaxy, we present this

---

12 STSDAS was developed at the Space Telescope Science Institute (STScI is operated by the Association of Universities for Research in Astronomy, Inc., for NASA).

13 Available at http://www.stsci.edu/documents/dhb/web/c32_wfpc2dataanal.fm1.html.
information in the form of pCMDs. Figure 2 shows the NUV-(NUV-I\textsubscript{814}) pCMDs for NGC 6753 and NGC 6782. There are two or three bright foreground stars in each image that can create spurious features in the pCMDs (one is visible in the lower right corner of the image sections of NGC 6782 in Fig. 1). After masking out these bright stars, we plot all pixels with at least three counts (DN) in both the sky-subtracted, red-leak-corrected NUV and the I\textsubscript{814} images. In practice, the signal limit is always reached in the NUV image first. The WFPC2 Handbook (Biretta et al. 2000) gives an effective gain of 6.90 ± 0.32 electrons DN\textsuperscript{-1} and a read noise of 5.22 electrons for WF3 at gain 7. Our data were obtained at a detector temperature of \(-88^\circ\text{C}\), giving a dark current of 0.0045 electrons s\textsuperscript{-1}. These, plus our measured sky brightness in the NUV (see Table 4) and exposure times (see Table 2), allow us to compute the signal-to-noise ratio (S/N) in the NUV for a limiting number of 3 DN pixel\textsuperscript{-1}. For NGC 6753 (two 950 s exposures), this works out to S/N \approx 4.0. For NGC 6782 (three 500 s exposures), we have S/N \approx 5.0.

On the right-hand margins of Figure 2 we show the absolute magnitude scale for the NUV data for our assumed distances (see Table 1). For these distances, a WF3 pixel subtends approximately 20 pc for NGC 6753 and 25 pc for NGC 6782. The data have been corrected for foreground extinction using the extinction map of Schlegel, Finkbeiner, & Davis (1998) and the reddening law of Cardelli, Clayton, & Mathis (1989). The arrows in Figure 2 show reddening vectors for 1 mag of absorption in \(A_{\text{NUV}}\), following the Cardelli et al. (1989) reddening law.

There are a number of clear features in the pCMDs. Plumes of very red pixels (shown as black points in Fig. 2)
extend up to $M_{\text{NUV}} \approx -10$ in both galaxies. For NGC 6753 this plume is at $(\text{NUV} - I_{814}) \approx 3.5 \pm 0.25$, while for NGC 6782 it is at $(\text{NUV} - I_{814}) \approx 3.3 \pm 0.3$. Although this difference in color is not statistically significant, we speculate that it may be due to a slightly higher internal extinction in NGC 6753, as NGC 6753 is a later type galaxy than NGC 6782. These red plumes are likely to be due to areas that are dominated by the old stellar populations, with little or no ongoing massive star formation (see § 5.3).

Both systems show two separate and parallel blue plumes in the pCMDs, separated by roughly a magnitude in $(\text{NUV} - I_{814})$ color. These plumes extend up to $M_{\text{NUV}} \approx -12$ in both galaxies, although they cease to be distinct from one another brighter than $M_{\text{NUV}} \approx -10.5$ for NGC 6753. In both galaxies, we shall refer to the redder of the blue plumes as “blue plume 1” (shown as red points in Fig. 2) and the bluer of the blue plumes as “blue plume 2” (shown as green points in Fig. 2). In Figure 2a, the horizontal line at NUV = 22.2 marks the bright limit at which the blue plumes appear separate. Points above this line are plotted in teal in Figure 2a. The relative density of points in the two plumes is very different in the two galaxies. In NGC 6753 blue plume 1 is the more densely populated, while in NGC 6782 it is blue plume 2. The plumes run nearly parallel to the extinction vector. This means that the distribution of pixels within a given plume may be driven entirely by the amount of extinction in the direction of that pixel. It also means that the separation between the plumes cannot be an extinction effect.

There are also collections of pixels blueward of the prominent blue plumes in both galaxies (shown as blue points in Fig. 2). In NGC 6782, this population is clearly separated in $(\text{NUV} - I_{814})$ from blue plume 2. In NGC 6753, it forms a blue extension of blue plume 2 and is not clearly separated in color. Finally, in NGC 6753 there is a spur emerging from the blue edge of the red plume (shown as purple points in Fig. 2a), at $(\text{NUV} - I_{814}) \approx 2.5 - 3.0$, extending up to $M_{\text{NUV}} \approx -9.5$ and running parallel to the blue plumes.

We have added solid lines to Figure 2 to demarcate these regions of the pCMDs. We have also used these boundaries
to separate the pixels according to physical location in their host galaxies. We show these distributions in Figure 3 for NGC 6753 and in Figure 4 for NGC 6782, with the same color coding as in Figure 2 (the red-plume pixels plotted in black, the blue-plume-1 pixels plotted in red, the blue-plume-2 pixels plotted in green, and the very blue pixels plotted in blue). A truly remarkable pattern emerges: the features that are isolated in the pCMDs represent very sharply bounded radial regimes in both galaxies, and in both cases there is a strict progression in color, with the reddest features in the pCMDs coming from the centers of the galaxies and the bluest features from the largest radii. In NGC 6753, blue plume 1 corresponds to pixels in the inner ring (Buta 1995). The blue-plume-2 pixels are from the spiral arms outside this inner ring. In NGC 6782 both the blue plumes correspond to pixels in the nuclear ring (Buta 1995), the separation between the plumes being the strong absorption lanes visible in Figure 1. The very blue pixels in NGC 6782 are in the inner ring (Buta 1995). The separation of the blue plumes in color space is a very curious feature. Metallicity gradients, dust distribution patterns, and smooth radial declines in $I_{814}$-band surface brightness can all produce a blueing trend with increasing radius, but the gaps between features in color space indicate that there is more to the story than this.

In Figure 5 we show $NUV - I_{814}$ magnitude-magnitude plots (expressed as mag pixel$^{-1}$) for the two galaxies. These plots indicate that the pixels in a given blue plume have a nearly constant $I_{814}$-band surface brightness and a large range in NUV surface brightness. Conversely, in both galaxies the two blue plumes have nearly the same range in NUV surface brightness and are separated by about a magnitude in $I_{814}$-band surface brightness. Thus, the separation of the blue plumes is due to drops in the $I_{814}$-band surface brightness at particular radii. Further, as the NUV surface brightness distribution is the same in the two plumes, this means that the drops in the $I_{814}$-band surface brightness have essentially no effect on the absolute strength of the ongoing unobscured star formation. We speculate that the abrupt changes in the $I_{814}$-band surface brightness are due to dynamical effects in the disks of the galaxies that govern the long-term global star formation in the disks. We discuss this matter further in § 5.

4. MUV-NUV-I COLOR MAP FOR NGC 6782

As we obtained an MUV image of NGC 6782, in addition to the NUV and $I_{814}$-band images, we examined the (MUV−NUV)−(NUV−$I_{814}$) color-color plot. Unfortunately, there are very few pixels with a significant number of counts in the MUV image. All the photons are from the star-forming ring (see Fig. 1). We restrict our analysis to only those pixels with at least 3 DN in the NUV ($S/N \geq 5.0$) and $I_{814}$-band images and 2 DN ($S/N \geq 3.6$) in the MUV image (the formal limit of 3 DN on the $I_{814}$ image is never reached in practice). When we look at the distribution of
these pixels in physical space, we find that they are from three spatially distinct regions in the star-forming ring. One
is in the region of the ring that corresponds to blue plume 1
(the patch on the inner edge of the visible ring, at about two
o’clock, in the MUV image shown in Fig. 1), while the other
two are in the region corresponding to blue plume 2 (the
patches at about five and ten o’clock in the MUV image).
The color-color plot, shown in Figure 6, reveals that the ring
has a foreground-corrected \( \frac{M_{\text{MUV}}}{C_{\text{NUV}}} \frac{C_{\text{I}}}{C_{\text{M}}^{0.25}} \).

The different symbols indicate which patch the pixels come
from, with the red crosses corresponding to the pixels from
the inner part of the ring (the patch at about two o’clock, in
the MUV image) and the green triangles and circles corre-
sponding to the pixels from the outer part of the ring (the
patches at about five and ten o’clock, respectively, in the
MUV image). The crosses are systematically redder in
\( \frac{\text{NUV}}{C_{\text{I}}^{0.814}} \) than the circles and triangles, as would be
expected given that they come from the redder plume. The
arrow in the upper right corner of Figure 6 is a reddening vector for 1 mag of absorption in \( m_{\text{NUV}} \), using the Cardelli
et al. (1989) reddening law. The thin line shows the model
color vector of a mixture of young and old populations
discussed in § 5.3.

There is evidence for a trend with \( \text{NUV} - I_{\text{814}} \) color such
that the bluest pixels in \( \text{NUV} - I_{\text{814}} \) are the reddest pixels in
\( \text{MUV} - \text{NUV} \) (that is, in the opposite sense to the model
color vector). Majewski (1988) saw a similar trend in his
optical and NIR data for the starburst ring galaxy 52W036.

He noted that the bluest pixels in \( U-B \) were the reddest
pixels in \( V-K \). For our data, the Spearman and Kendall
rank correlation tests both indicate that this trend is signifi-
cant at greater than the 99.9% level for the full sample (83
data points). If we restrict the test to just the pixels from blue
plume 2 (56 points), the result holds with even higher signifi-
cance. The trend breaks down when we consider only the
pixels from blue plume 1 (27 points). This may be due to the
small number of pixels detected in blue plume 1, or it may
be that the trend is an astrophysical one that is driven by the
young stellar population. In this case, the trend could disap-
pear for blue plume 1 as a result of increased dilution from
the old stellar population.

While we do not feel that our data warrant a detailed
investigation of this point, two possible causes for the
observed trend are contamination of the \( I_{\text{814}} \) fluxes by the
emission lines of [S iii] from H ii regions (e.g., Garnett 1989;
Castellanos, Diaz, & Terlevich 2002) and the presence of a
significant number of late-type supergiants in the most
actively star-forming regions (e.g., Schaller et al. 1992;
Rhoads 1998). Both of these will lead to enhanced red emis-
sion in the regions of the youngest stellar populations.
Majewski (1988) suggested that his result was due to the
presence of late-type supergiants as well. This interpretation
is bolstered by a consideration of the integrated colors of
star clusters in the Magellanic Clouds from the study of
Persson et al. (1983). A plot of \( U-B \) against \( V-K \) shows
a U-shaped distribution of points, with the reddest clusters.
in \((V-K)\) having either the reddest \((U-B)\) colors (for the oldest clusters) or the bluest \((U-B)\) colors (for the youngest clusters). The \(K\) band also contains the \(\text{Br}\gamma\) (2.16 \(\mu\)m) emission line, which could also lead to (or enhance) the observed trends.

5. DISCUSSION

5.1. Pixel CMDs

The technique of using pCMDs to study the structure and stellar populations of galaxies is not common, but we are not the first to use it. Bothun (1986) presented an analysis of a \(B-(B-R)\) pCMD of NGC 4449. His data show a similar blue-plume structure to that which we find for NGC 6753 and NGC 6782. There is little evidence for a red plume in Bothun’s data, but NGC 4449 is a much later type galaxy than our targets and thus has a relatively more dominant young population. Moreover, Bothun’s data are in the \(B\) and \(R\) bands, which do not provide as clean a spectral discriminant between hot and cool stars as do our NUV and \(I_{814}\)-band data. Bothun (1986) found a spatial segregation in color, analogous to what we see in our data (see his Fig. 8), but in the opposite sense: the bluest pixels in NGC 4449
are along the central star-forming ridge (see the image in Sandage & Bedke 1994), with increasingly red pixels at larger radii. This difference again follows from the much later Hubble type of NGC 4449 compared to our targets: NGC 4449 is an irregular, with a central band of vigorous star formation. Our earlier type spirals both have central bulges, with no significant current central star formation.

As noted in § 4, Majewski (1988) presented a $(U-B)$-$(V-K)$ pixel color-color map of the starbursting ring galaxy associated with the radio source 52W036 and noted that the reddest pixels in $(V-K)$ were the bluest pixels in $(U-B)$. He also noted the general trend of increasingly blue color (for the $[U-B]$ color, in his case) with increasing radius. He ascribed this to a radial age gradient in the starbursting ring.

The use of pCMDs was also discussed by Kron, Annis, & Wilhite (2000). They present $g-(g-r)$ pCMDs for a spiral (NGC 4030) and an elliptical (NGC 4753). Despite the smaller color baseline and poorer spatial resolution of their data, they find structures similar to what we see in our data. They also note that pixels from a given blue plume in NGC 4030 all come from the same annulus. Thus, they see the same spatial correlation between location and color that we do and reach the same basic conclusions about its origin.

5.1.1. Comparison with Radial Profiles

One measure of the importance of ongoing star formation in a disk is an estimate of how much of the disk is currently populated by young stars. The fraction of pixels in the inner ring of NGC 6753 (the red zone in Fig. 3) that are above a minimum threshold of 3 DN in the NUV is about 60%. For the nuclear ring of NGC 6782 (the red and green zones in Fig. 4) the fraction of pixels above this threshold is about 50%. If we extrapolate the relationship between NUV and $I_{814}$ surface brightness for the red plumes from Figure 5, we can estimate that the underlying old populations in these regions will have NUV $\approx 26$. This works out to less than 1 DN in the NUV. Thus, a threshold of 3 DN selects pixels in which the NUV is dominated by the unobscured young population. This implies that at least 50%-60% of the disk surface area is engaged in ongoing star formation in the most actively star-forming radial zones in our targets. This is really a lower limit, as it ignores the (obviously present) effects of extinction.

A more traditional way of examining the properties of galaxy disks is the use of radial surface brightness and color profiles. In Figure 7 we show NUV (circles) and $I_{814}$-band (crosses) surface brightness profiles and (NUV–$I_{814}$) color profiles for NGC 6753. The profiles were generated using elliptical annuli, with the (assumed constant) ellipticities measured from the F814W image at a radius of about 50″ from the nucleus. NGC 6753 shows a peak in $I_{814}$ surface brightness and then a general decline with radius. There are changes in slope in the surface brightness profile at about 10″ and 18″. The rate of decline of the $I_{814}$ surface brightness increases at just beyond these radii. The NUV surface brightness profile shows strong enhancements at radii just...
inside the slope changes of the $I_{814}$ surface brightness profile. These show up as strong bluward peaks in the color profile and correspond to the two blue plumes in the pCMD. The feature at about 20$''$ corresponds to the high points in Figure 3, and the feature at 18$''$ is the strong spiral arms plotted in green in Figure 3.

Figure 8 shows the same plots for NGC 6782. The $I_{814}$ (crosses) surface brightness profile of NGC 6782 shows less structure than that of NGC 6753. There is one clear break at about 20$''$. The NUV (circles) surface brightness profile has a much stronger enhancement at this radius, and the color profile has a strong blue feature here. The NUV surface brightness profile also has a strong enhancement at about 5$''$, which shows up as a dramatic blue spike in the color profile. These are due to the two rings of star formation, with the feature at 5$''$ plotted in Figure 4 as red and green points and the feature at 20$''$ plotted in Figure 4 as blue points.

The behavior of the radial profiles of both galaxies supports the conclusion that we drew from Figure 5: regions of strong, unobscured, ongoing star formation (as traced by localized enhancements in the NUV surface brightness) are associated with regions of increased rate of decline in the $I_{814}$-band surface brightness. It is these discontinuities in the $I_{814}$-band surface brightness that drive the separations between the plumes we see in the pCMDs. The power of a pixel analysis is that it demonstrates that the range of NUV surface brightness is the same in each region of strong star formation (see Fig. 5). That is, the maximum rate of localized star formation is not a strong function of the underlying distribution of old stellar mass. This point is lost in a traditional profile analysis.

5.1.2. Binned Pixel CMDs

Our pCMDs are noisy. In particular, they suffer from obvious discreteness noise due to the low count rate in the NUV data. Binning the data makes the trade-off of lowering the spatial resolution while allowing us to probe fainter surface brightness levels at a given S/N. We made $2 \times 2$ and $3 \times 3$ binned images of both galaxies and generated pCMDs from the binned images. We imposed a limit of $S/N \geq 3$ pixel$^{-1}$ on the binned pCMDs. For NGC 6753 this translates to a minimum of 4 DN per $2 \times 2$ binned pixel and 6 DN per $3 \times 3$ binned pixel. This means that the $2 \times 2$ binned image probes roughly 1.2 mag fainter in surface brightness than does the unbinned image, while the $3 \times 3$ binned image goes roughly 1.6 mag fainter. For NGC 6782 the limits are 3 DN per $2 \times 2$ binned pixel and 5 DN per $3 \times 3$ binned pixel. This means that the $2 \times 2$ binned image probes roughly 1.5 mag fainter in surface brightness than does the unbinned image, while the $3 \times 3$ binned image goes roughly 1.8 mag fainter. For NGC 6782 the limits are 2 DN per $2 \times 2$ binned pixel and 3 DN per $3 \times 3$ binned pixel. This means that the $2 \times 2$ binned image probes roughly 1.5 mag fainter in surface brightness than does the unbinned image, while the $3 \times 3$ binned image goes roughly 1.8 mag fainter. We present the binned pCMDs in Figure 9. As in Figure 2, interior to the left-hand axis, we plot the surface brightness in mag arcsec$^{-2}$. Figures 9a and 9b show the $2 \times 2$ and $3 \times 3$ binned pCMDs for NGC 6753, respectively, while Figures 9c and 9d show the $2 \times 2$ and $3 \times 3$ binned pCMDs for NGC 6782, respectively. NGC 6753 now shows evidence for at least four blue plumes. The improvement in the pCMD for NGC 6782 is less dramatic, but the blue plumes are better defined and extend to much fainter surface brightness than in the unbinned data.
Fig. 9a—Binned NUV-(NUV−[Ks]) pCMDs for (a) NGC 6753 with 2 × 2 pixel binning, (b) NGC 6753 with 3 × 3 pixel binning, (c) NGC 6782 with 2 × 2 pixel binning, and (d) NGC 6782 with 3 × 3 pixel binning. In all cases, the numbers interior to the left-hand axis show the NUV surface brightness in mag arcsec$^{-2}$. 
The binned pCMDs for NGC 6753 (Figs. 9a and 9b) show the same basic features at high surface brightness as does the unbinned pCMD. The blue plumes are a bit more diffuse. At lower surface brightness, some interesting features emerge. The red plume has a clear faint limit (at NUV $\approx 23.5$ in Fig. 9b), much brighter than the S/N cutoff imposed. This limit is the minimum NUV surface brightness of the old population in the bulge region of NGC 6753. There is also a faint limit to the inner blue plume that reflects the minimum NUV surface brightness of the inner ring, at NUV $\approx 24$ in Figure 9b. Given our assumed distance (see Table 1), this is roughly the expected apparent magnitude of a single O5 main-sequence star. The distribution of pixels blueward of the blue plume 2 in Figure 2a (the blue region in Fig. 4) is a coherent plume in Figures 9a and 9b. These pixels are due to the outer star-forming regions in the disk.

The binned pCMDs for NGC 6782 (Figs. 9c and 9d) show the truncation of the red plume, similar to what is seen in NGC 6753. They also reveal the benefit of high angular resolution: the two distinct blue plumes in Figure 2b are merged together in the binned pCMDs. However, the star-forming knots associated with the inner ring (not the nuclear ring!) form a well-developed blue plume in Figure 9c, running from [NUV $\approx 24.6$, (NUV $-I_{814}) \approx 1.3$] to [NUV $\approx 22$, (NUV $-I_{814}) \approx -0.4$]. Only the very brightest knots associated with this plume show up in the unbinned pCMD.

5.2. Disk Dynamics

The NUV light traces the distribution of ongoing unobscured star formation in our targets. In both galaxies, the majority of the ongoing star formation occurs in small radial ranges. That is, the current star-forming properties of the disks are governed by the gravitational dynamics of the disks. Both NGC 6753 and NGC 6782 are in the Catalog of Southern Ringed Galaxies (Buta 1995), in which they are classified as (R')SA(r)b (NGC 6753) and (R')SB(r)0/a (NGC 6782). Thus, there is significant prior work on the internal dynamical state of both systems.

In both galaxies, there is no evidence for current star formation in the inner parts of the galaxies (the red plumes). Buta & Crocker (1993) have argued that the onset of strong star formation in NGC 6753 (that is, the inner boundary of the region that is responsible for blue plume 1) occurs at the inner Lindblad resonance (ILR). The inner ring in NGC 6753 is the structure that marks the spatial boundary between the pixels forming the two blue plumes. Crocker, Baugus, & Buta (1996) identify this as the location of the 4:1 ultraharmonic resonance (UHR). At this point, the long-term star formation rate drops abruptly, and blue plume 2 shows pixels of ongoing star formation in the disk outside the UHR. The very blue pixels show the knots of current star formation in the outer ring, which is most likely associated with the corotation radius (CR).

The bright star-forming ring that is so prominent in our NUV image of NGC 6782 is not the inner ring but is actually a third, nuclear ring. Byrd et al. (1994) associate the nuclear ring with the ILR. The blue plumes correspond to the inside and outside of the dust lane associated with this nuclear ring that surrounds the nuclear bar. The $I_{814}$ band surface brightness drops abruptly at the radius of the dust lane, and outside this region current star formation ceases entirely. The outer blue plume is due to a small number of star-forming knots in the inner ring that is associated with the terminus of the inner bar. The bar is visible in our $I_{814}$ image and is prominent in ground-based NIR images (Eskridge et al. 2002). Byrd et al. (1994) associate the inner ring with the UHR.

5.3. Stellar Populations

Our data show evidence for dynamically triggered ongoing star formation added onto the accumulated older stellar populations of the target galaxies. In order to put this interpretation on a firmer footing, we compare our data to model properties of single stars, composite stellar populations, and observations of young stellar clusters.

5.3.1. Comparisons with Stellar Models

Romaniello et al. (2002) have published model stellar color-temperature data for a number of HST/WFPC2 bandpasses. Figure 10 shows the predicted relationship between effective temperature and our (NUV $-I_{814}$) color for both main-sequence (log $g = 4.5$) and giant (log $g = 3$) stars. The reddest colors observed in our pCMDs for both NGC 6753 and NGC 6782 are (NUV $-I_{814}) \approx 4$. The models of Romaniello et al. (2002) indicate that such a color is appropriate for stars with $T_{\text{eff}} \approx 5000$ K, i.e., early K V or late G III stars. The turnover of an old stellar population dominates its UV light, and an early K turnoff is appropriate for the stellar population that dominates the centers of early- to mid-type spirals. As this is exactly where the red-plume pixels are located, this argues strongly that the red plumes are due to the old stellar population.

![Fig. 10.—Model (NUV $-I_{814}$) colors for stars, plotted against stellar effective temperature. The solid line shows the predicted relationship for main-sequence stars, and the dotted line for giants.](image-url)
The bluest colors predicted in the Romaniello et al. (2002) models are \((\text{NUV}/\text{C}0 \text{I})_{814} \approx -3\), for O stars \((T_{\text{eff}} \approx 5 \times 10^4 \text{ K})\). The bluest pixels in our pCMD for NGC 6753 are also \((\text{NUV}/\text{C}0 \text{I})_{814} \approx -3\), supporting our argument that the light from these pixels is dominated by unobscured ongoing massive star formation. The bluest pixels in the pCMD for NGC 6782 are only \((\text{NUV}/\text{C}0 \text{I})_{814} \approx -1\). If the light from these pixels is dominated by current/recent star formation, this implies that the maximum stellar temperature in NGC 6782 is only \(T_{\text{eff}} \approx 1.3 \times 10^4 \text{ K}\), corresponding to late B stars. An alternative explanation is that even the bluest pixels in NGC 6782 have a substantial contribution to their light from the older, redder stellar population. If we assume that the bluest pixels in NGC 6782 have all their NUV light coming from O stars, the absolute magnitudes of those pixels \((M_{\text{NUV}} \approx -12)\) require about 20–25 O5 stars per pixel. The colors of the pixels are \((\text{NUV}/\text{C}0 \text{I})_{814} \approx -1\), so \(M_I \approx -11\). The Romaniello et al. (2002) models indicate that these stars would have an integrated \(I_{814}\)-band absolute magnitude of \(M_I(<\text{young}) \approx -9\). This means that the total contribution of the underlying old population would need to be \(M_I(<\text{old}) \approx -10.8\). Assuming this light to be produced by K5 III stars leads to the requirement of about 5000 such stars per pixel. The predicted integrated NUV absolute magnitude of 5000 K5 III stars is only \(M_{\text{NUV}}(\text{old}) \approx -5.3\), a negligible contribution to the total \(M_{\text{NUV}} \approx -12\). Thus, the O stars account for all the NUV light, and the K stars dominate the \(I_{814}\)-band light.

### 5.3.2. Comparisons with Simple Stellar Population Models

We can approach the problem from a different direction using the spectral evolution models of Bruzual & Charlot (1993). The question we wish to probe is how mixing various amounts of a young stellar population with an underlying old population will affect the predicted \((\text{NUV}/\text{I})_{814}\) color of the resulting composite stellar population. We adopt the Bruzual & Charlot (1993) 10 Gyr model, with a low-mass cutoff of \(0.1 M_{\odot}\), as our old model and the 1 Myr model, with a low-mass cutoff of \(0.1 M_{\odot}\) and high-mass cutoff of \(125 M_{\odot}\), as our young model. We combine these models with variable weights and convolve the combinations with the sensitivity curves for our filters, using SYNPHOT. We picked a constant \(I_{814}\)-band magnitude and determined the predicted \((\text{NUV}/\text{I})_{814}\) color for a range of weights. As we constrain the \(I_{814}\)-band magnitude, the weights reflect the input contributions of the young and old populations to the desired \(I_{814}\)-band magnitude. The results of this experiment are given in Table 5 and shown in Figure 11.

| Old Weight | Young Weight | \((\text{NUV}/\text{I})_{814}\) | \((\text{NUV}/\text{NUV})\) |
|------------|--------------|-----------------|-----------------|
| 1          | 0            | 3.46            | 1.42            |
| 0.99999    | 0.00001      | 2.99            | 0.38            |
| 0.999      | 0.001        | 1.47            | -0.29           |
| 0.99       | 0.01         | -0.67           | -0.42           |
| 0.9        | 0.1          | -2.10           | -0.44           |
| 0.9        | 0.1          | -2.46           | -0.44           |
| 0.9        | 1            | -2.50           | -0.44           |

Fig. 11a—NUV-(NUV-I) pCMDs for (a) NGC 6753 and (b) NGC 6782, as in Fig. 2. The dotted lines show the effect of mixing small amounts of a young population with an underlying old population. The circles show the knot points given in Table 5.
old populations with the constraint that $I_{B14} = 22.8$ (roughly the magnitude of the base of blue plume 1). The circles show the knot points, with a pure young population at the top, and an order-of-magnitude decrease in the weight of the young population for each circle. The circle at $[(NUV - I_{B14}) = 1.5, NUV = 24.3]$ results from a young population that contributes only $10^{-4}$ of the $I_{B14}$ light. Figure 1b shows the same models overlayed on the NGC 6782 pCMD, with the constraint shifted to $I_{B14} = 21.8$. The knot point at $[(NUV - I_{B14}) = 1.5, NUV = 23.3]$ results from a young population that contributes only $10^{-4}$ of the $I_{B14}$ light.

The model runs nearly parallel to the blue plumes in NGC 6753. The model and the data are a bit more skewed for NGC 6782, but in both cases the loci defined by these simple models are good representations of the distributions of the points in the blue plumes of the pCMDs. Thus, one can produce the observed distribution of points in the pCMDs by either simple mixtures of young and old populations or pure young populations and reddening (although the existence of an old population follows from the $I_{B14}$-band morphologies). Note that this also means, at least in the case of NGC 6753, that the separation between the plumes is not due to variations in the current level of star formation laid atop a constant old population. This will move a given point along a plume but will not move it from one plume to another.

In Figure 6 we show the locus of the mixture model, as a solid line, in the $(M_{UV} - NUV)$-$([NUV - I_{B14}])$ color-color plane. The two large squares show the predicted colors for young population fractions of $10^{-4}$ and $10^{-3}$ (see Table 5). The points generally scatter around the model and indicate that a small fraction of ongoing star formation plus substantial and variable reddening can produce the colors we see. We note that the generally redder colors of the pixels from the inner part of the nuclear ring can easily be due to either reddening or a larger contribution from the old stellar population.

5.3.3. Comparisons with Observations of Young Stellar Clusters

A final test of our basic picture is provided by the data of Harris et al. (2001), who provide F300W and F814W observations of young star clusters in M83. They estimate the ages of these clusters to be in the range 2–50 Myr. In Figure 12 we show the $(NUV - I_{B14})$ colors of the M83 star clusters plotted against their ages. The youngest M83 clusters are generally the bluest and have typical integrated colors of $(NUV - I_{B14}) \approx -3.5$, consistent with the bluest plumes in NGC 6753. The oldest clusters have colors of $(NUV - I_{B14}) \approx -1.5$, more similar to the bluest plumes we see in NGC 6782. These tests show that the redder colors of the blue plumes in NGC 6782, compared to NGC 6753, can be due to either an older starburst population or a larger fraction of old stars mixed with a zero-age starburst population. We believe that the latter interpretation is more likely correct, as the active star formation in NGC 6782 occurs in the very inner part of the galaxy and NGC 6782 is an earlier type system than NGC 6753.

6. SUMMARY AND CONCLUSIONS

We have analyzed HST/WFPC2 NUV and $I_{B14}$ images of the face-on spiral galaxies NGC 6753 and NGC 6782. We use these images to construct NUV-$(NUV - I_{B14})$ pCMDs for these galaxies. Our data are a set of aligned HST/WFPC2 images, with the images for a given galaxy all obtained in the same orbit. Thus, we have sets of well-aligned, undersampled images. This is a real advantage for pixel mapping, as it results in essentially statistically independent pixels. One can thus treat each pixel as a pseudo-star cluster. This work opens the possibility of studying the detailed interplay between the star formation history and dynamics of nearby disk galaxies. As the $I_{B14}$-band light is mainly from the old population, it is a good tracer of the stellar mass. The $I$-band mass-to-light ratio is between 1 and 2 in solar units and is not a strong function of age for populations older than 1 Gyr or so. Thus, the $(NUV - I_{B14})$ color is, in effect, a measure of the current unobscured star formation rate per unit stellar mass.

Our pCMDs reveal clear, separated plumes of pixels. Each of these plumes have strongly varying NUV surface brightness and nearly constant $I_{B14}$ surface brightness. The maximum and average NUV surface brightnesses are the same from plume to plume. It is the decline with increasing radius of the maximum $I_{B14}$ surface brightness that causes the separation between the plumes. In both galaxies, the plumes correspond to distinct, sharply bounded radial ranges, with the $(NUV - I_{B14})$ color at a given NUV surface brightness being bluer at larger radii. These plumes are parallel to both the reddening vector and simple models of mixtures of young and old populations. Thus, it is unclear from our data if the distribution of points in a given plume is primarily due to variations in reddening or in the relative importance of a young stellar population. Conversely, it is clear that neither reddening nor varying the importance of a young population can produce the separations between the plumes.

The $I_{B14}$ images, as well as radial surface brightness and color plots, indicate that the separate plumes are caused by discontinuities in the surface density of the old stellar population. These discontinuities are the result of the accumulated history of star formation in the disks of these galaxies. The current star formation, as traced by the NUV images, is clearly driven by dynamical triggers in both galaxies. NGC 6782 is a particularly clear example of this since all the current star formation, as traced by the NUV light, is associated with the nuclear and inner rings.
We have an MUV image of NGC 6782 that shows emission from the nuclear ring. We have used this to generate an (MUV−NUV)−(NUV−\text{\textit{I}}_{\text{B,4}}) pixel color-color diagram. The colors are generally consistent with a model that mixes a small fraction of a young stellar population with a dominant old population. Either variations in the relative strength of ongoing star formation or reddening can produce the scatter we see in the color-color plot. A curious feature of this diagram is that the bluest pixels in (MUV−NUV) tend to be the reddest pixels in (NUV−\text{\textit{I}}_{\text{B,4}}). This trend is statistically significant based on both the Spearman and Kendall rank tests. We speculate that it may be due to a combination of enhanced [S II] emission from H II regions and the red flux from late-type supergiants associated with very young stellar populations.

The sort of study we have done in this paper is now possible for a substantial number of galaxies as the result of our Cycle 9 (Windhorst et al. 2002) and 10 HST UV imaging programs.\footnote{Cycle 10 HST program 9124, “Mid-UV Snapshot Survey of Nearby Irregulars: Galaxy Structure and Evolution Benchmark”; PI: R. Windorst.} A more densely sampled spectral energy distribution would allow for more detailed stellar population modeling than the admittedly crude attempt we have made here (e.g., Frogel 1985). We are encouraged that the Hubble Heritage Team followed up our imaging of NGC 6782 with a multiband Heritage imaging program. The addition of just the remaining optical bandpasses (\textit{UBVR}) will allow a much more accurate disentangling of the various effects of age, extinction, metallicity, and the relative importance of different populations than has been possible here. One clear task for the future is to use the Heritage data to investigate the stellar populations and effects of dust in the disk of NGC 6782.

P. B. E. would like to thank the members of the Department of Astronomy at Ohio State University, where this project was begun. J. A. F. acknowledges the support of NASA Headquarters for publication funds while he is on leave there from OSU. J. A. F. thanks Sean Solomon for granting him Visiting Investigator status at DTM/CIW. L. D. M. acknowledges support from a Clay Fellowship from the Harvard-Smithsonian Center for Astrophysics. We thank R. Pogge for suggesting that [S II] emission could contribute to the effect mentioned in § 4. We also thank R. Kron for pointing out S. Majewski’s work on pixel mapping. This research has made use of NASA’s Astrophysics Data System Bibliographic Services and the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This work was supported in part by NASA Hubble Space Telescope grants HST-GO-08645* and HST-GO-09124* and the NASA Long Term Space Astrophysics grant NAG 5-6403 to the University of Virginia.

A more ambitious program for the future would be to observe these galaxies with the NICMOS or WFC3 on HST in order to obtain NIR colors and 2.29 \mu m CO index images. Broadband NIR imaging would provide data on the distribution of the old stellar populations that are essentially free from the effects of dust. The NIR CO index is an excellent diagnostic for the relative importance of late-type supergiants in an unresolved stellar population, as a result of its strong dependence on surface gravity (Baldwin, Frogel, & Persson 1973). Observations of nearby galaxies (Rhoads 1998) have shown that CO index measurements are a potentially powerful tool for studying the distribution of recent star formation in galaxies, as they are sensitive to the distribution of massive supergiants and are relatively unaffected by dust.

**REFERENCES**

Abraham, R. G., Ellis, R. S., Fabian, A. C., Tanvir, N. R., & Glazebrook, K. 1990, MNRAS, 308, 569
Baggett, W. E., Baggett, S. M., & Anderson, K. S. J. 1998, AJ, 112, 3046
Baldwin, J. R., Frogel, J. A., & Persson, S. E. 1973, ApJ, 184, 427
Biretta, J. A., et al. 2000, WFPC2 Instrument Handbook, Version 5.0 (Baltimore: STScI)
Block, D. L., Bertin, G., Stockton, A., Grosbol, P., Moorwood, A. F. M., & Peletier, R. F. 1994, A&A, 288, 365
Bothun, G. D. 1986, AJ, 91, 507
Bowyer, S., Sassee, T. P., Wu, X., & Lampton, M. 1995, ApJS, 96, 461
Bruzual, A. G., & Charlot, S. 1993, ApJ, 405, 538
Bushouse, H., & Simon, B. 1998, SYNPHOT User’s Guide (Baltimore: STScI)
Buta, R. 1995, ApJS, 96, 39
Buta, R., & Crocker, D. A. 1993, AJ, 105, 1344
Byrd, G., Rautiaine, P., Salo, H., Buta, R., & Crocker, D. A. 1994, AJ, 108, 476
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Cardiellos, M., Diaz, A. I., & Terlevich, E. 2002, MNRAS, 329, 315
Crocker, D. A., Baggs, P. D., & Buta, R. 1996, ApJS, 105, 353
de Grijs, R. 1998, MNRAS, 299, 595
de Jong, R. S. 1996, A&A, 313, 377
de Vaucouleurs, G., de Vaucouleurs A., Corwin, H. G., Jr., Buta, R. J., Paturel, G., & Fouque, P. 1991, Third Reference Catalogue of Bright Galaxies (Springer: New York) (RC3)
Eskridge, P. B., et al. 2002, ApJS, 143, 73
Frogel, J. A. 1985, ApJ, 298, 528
Frogel, J. A., Quillen, A. C., & Pogge, R. W. 1996, in New Extragalactic Perspectives in the New South Africa, ed. D. Block & J. M. Greenberg (Dordrecht: Kluwer), 65
Garnett, D. R. 1989, ApJ, 345, 282
Hackwell, J. A., & Schweizer, F. 1983, ApJ, 265, 643
Harris, J., Calzetti, D., Gallagher, J. S., III, Conselice, C. J., & Smith, D. A. 1990, AJ, 122, 1046
Holtzman, J. A., Burrows, C. J., Casertano, S., Hester, J. J., Trauger, J. T., Watson, A. M., & Worthey, G. 1995, PASP, 107, 1065
Kent, S. M. 1985, ApJS, 59, 115
Kinney, A. L., Calzetti, D., Bohlin, R. C., McQuade, K., Storchi-Bergman, T., & Schmitt, H. R. 1996, ApJ, 467, 38
Kormendy, J. 1977, ApJ, 217, 406
Kron, R. G., Annis, J., & Wilhite, B. C. 2000, BAAS, 32, 9.15
Kuchinski, L. E., Madonna, B. F., Freedman, W. L., & Tremwella, M. 2001, AJ, 122, 729
Kuchinski, L. E., et al. 2000, ApJS, 131, 441
Majewski, S. R. 1988, in Toward Understanding Galaxies at Large Redshift, ed. R. G. Kron & A. Renzini (Dordrecht: Kluwer), 127
Marcum, P. M., et al. 2001, ApJS, 132, 129
Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H.-W. 2002, AJ, 124, 266
Persson, S. E., Aaronson, M., Cohen, J. G., Frogel, J. A., & Matthews, K. 1983, ApJ, 266, 105
Rhoads, J. E. 1998, AJ, 115, 472
Romaniello, M., Panagia, N., Scuderi, S., & Kirshner, R. P. 2002, AJ, 123, 915
Sage, L. J., & Solomon, P. M. 1989, ApJ, 342, L15
Sandage, A., & Bedke, J. 1994, The Carnegie Atlas of Galaxies (Washington: Carnegie Inst.-Washington)
Schaller, G., Schuehrer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Walterbos, R. A. M., & Kennicutt, R. C., Jr. 1987, A&A, 69, 311
Windhorst, R. A., et al. 2002, ApJS, 143, 113
Yahil, A., Tamman, F. A. & Sandage, A. 1977, ApJ, 217, 903
Zwicky, F. 1955, PASP, 67, 232