The Astrophysical Journal, 395: L45–L48, 1992 August 10

ULTRAVIOLET IMAGING OF OLD POPULATIONS IN NEARBY GALAXIES

Robert W. O'Connell,[1] Ralph C. Bohlin,[2] Nicholas R. Collins,[3] Robert H. Cornett,[3] Jesse K. Hill,[3] Robert S. Hill,[3] Wayne B. Landsman,[3] Morton S. Roberts,[4] Andrew M. Smith,[5] and Theodore P. Stecher[5]

Received 1992 March 31; accepted 1992 May 14

ABSTRACT

We analyze UV imagery of two Sb bulges and two E galaxies obtained with the Ultraviolet Imaging Telescope during the *Astro-1* mission. The UV brightness of these systems is not produced by recent massive star formation. Instead, it must originate in relatively low-luminosity objects, probably low-mass, post–giant-branch stars. We find extended, large-amplitude UV color gradients, which are probably related to abundance gradients within the galaxies. M32 has a color gradient opposite to the other three objects, possibly because of an intermediate-age population.

Subject headings: galaxies: individual (M31, M32, M81, NGC 1339) — galaxies: photometry — galaxies: stellar content — ultraviolet: general

1. INTRODUCTION

One of the earliest surprises of satellite ultraviolet astronomy was the discovery by *OAO 2* of a hot stellar component in elliptical galaxies and spiral bulges (Code 1969; Code & Welch 1979). These old, metal-rich systems had not been expected to contain appreciable numbers of stars hotter than their main-sequence turnoffs ($T_e \sim 5600$ K). Nevertheless, *OAO* energy distributions in the far-UV (120 nm $< \lambda <$ 200 nm) for nearby E galaxies and spiral bulges exhibited the steep rise to shorter wavelengths characteristic of stars with $T_e \gtrsim$ 20,000 K. This UV-excess (UVX) or "UV rising branch" population was confirmed by later *ANS* and *IUE* observations (e.g., Wu et al. 1980; Norgaard-Nielsen & Kjærgaard 1981; Oke, Bertola, & Capaccioli 1981; Bertola, Capaccioli, & Oke 1982). The two most likely origins for the UVX light were first proposed by Tinsley (1972) and Hills (1971), respectively: (1) *massive OB stars*, formed at a low rate during the past $\sim$50 Myr, presumably from hot gas lost during giant-branch evolution, and (2) *old, low-mass, post–giant-branch stars* in advanced evolutionary phases. The implications of these two interpretations differ considerably: in the former, the UVX is related to gas cycling and is therefore a probe of the interstellar "ecology" of old populations (Mathews 1990); in the latter, the UVX stars are the descendants of the dominant old population and may offer clues to its age, abundances, and other properties.

The balance of the evidence available to 1988 favored the low-mass interpretation. Light profiles within the $r \leq 10''$ region covered by the *IUE* aperture indicated that the far-UV light is distributed roughly like the optical light and, therefore, probably originates in a component with dynamics characteristic of the old population (Oke et al. 1981; Welch 1982; Deharveng et al. 1982; O'Connell, Thuan, & Puschell 1986). UV imaging of the bulge of M31 with a rocket prototype of the Ultraviolet Imaging Telescope (Bohlin et al. 1985), which yielded $\sim 18''$ resolution and an 80′ field of view, revealed no evidence for the presence of main-sequence O stars. Furthermore, the strong C IV and Si IV absorption features expected from a young population are absent in the far-UV spectra of M31 (Welch 1982). Burstein et al. (1988) analyzed a carefully assembled set of *IUE* spectra for E galaxies and concluded (1) that the spectral slope of the UVX component is roughly constant from object to object but that its amplitude varies by over a factor of 10; (2) that more metal-rich nuclei (as measured by the Mg_2 index) have stronger UVX components; and (3) that systems with unambiguous evidence for recent star formation have distinctly flatter UV spectra, indicative of a larger range of temperature than is found in the UVX systems. These features do not entirely exclude massive stars but are more readily understandable if the UVX originates in low-mass stars.

Unfortunately, the *IUE* spectra do not yield sufficient information to choose among the large variety of low-mass candidates. The leading contenders for some time were post–asymptotic giant branch (PAGB) stars (Schönberner 1983), which evolve to very high temperatures following loss of their envelopes near the tip of the asymptotic giant branch (AGB). However, PAGB objects probably lack sufficient H and He fuel to produce the stronger UV upturns, and stars which move to high temperatures at somewhat earlier evolutionary stages are more likely candidates (see Greggio & Renzini 1990 for a review). These include the post–early AGB (PEAGB) stars and "extreme–horizontal-branch" (EHB) stars (which never reach the AGB after central helium exhaustion). As explained by Greggio & Renzini, it is presumed that the total UV output of a population is an increasing function of metal abundance primarily because the rate of mass loss on the giant branch increases with metallicity. However, age may also be a factor, since the larger the mass of the stars at the base of the giant branch (and hence the younger they are), the lower the net UV output.

The Ultraviolet Imaging Telescope (UIT) of the *Astro-1* Spacelab payload is well suited to study the UVX problem by virtue of its combination of a large field of view (40′ diameter) and good resolution ($\sim 3''$). Several E galaxies and spiral bulges

[1] Astronomy Department, University of Virginia, P.O. Box 3818, Charlottesville, VA 22903.

[2] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218.

[3] Hughes/STX, Code 681, Goddard Space Flight Center, Greenbelt, MD 20771.

[4] National Radio Astronomy Observatory, Edgemont Road, Charlottesville, VA 22903.

[5] Code 680, Goddard Space Flight Center, Greenbelt, MD 20771.

were observed during the 1990 December *Astro-1* mission with the intent of searching for massive star complexes and studying spatial gradients on large scales. We report here on a preliminary analysis of four bright systems spanning a large range of luminosity and metal abundance.

2. OBSERVATIONS AND DATA REDUCTION

The design and on-orbit performance of the UIT are described by Stecher et al. (1992). UV images of M32 (E2) and NGC 1399 (E1) and the bulges of the Sb spirals M31 and M81 were obtained. Only the longest exposures (ranging from 304 to 1454 s) in the two broadest filters (A1 and B1) are described here. The far-ultraviolet (FUV) band is centered at 152 nm and has a bandwidth of 35 nm. For a flat energy distribution, the centroid of the near-ultraviolet (NUV) band (width 110 nm) is 249 nm, but this shifts to ~270 nm for the cool energy distributions of E galaxies. The images were digitized to 1".14 pixels, linearized, flat-fielded, and converted to flux using stars observed with *IUE*, as described in Stecher et al. (1992). The estimated uncertainty in the absolute flux calibration is 15%, but the normalization between the UIT and *IUE* flux scales appears to be considerably better (see below). We will quote magnitudes in the monochromatic system, defined as $m_\lambda = -2.5 \log F_\lambda - 21.1$, where the incident flux F_λ is in units of ergs s^{-1} cm^{-2} $Å^{-1}$. Typical resolution, determined by the telescope stability during the exposures, is FWHM ~ 3".

Sky background measurements were made in 15–20 positions free of stars near the edges of each frame. For M81 and NGC 1399, these are free of light from the galaxy itself. In the case of M31 and M32, some small contamination from the outer disk of M31 is likely present. For the M31 and M81 bulges, it would also be desirable to remove the underlying exponential disk contribution. This has not been attempted here, but tests using sky values up to ±0.7 mag different from nominal show that the colors and gradients obtained over the inner regions are not strongly affected by background errors. The UV sky background at high Galactic latitudes is quite faint, as expected (e.g., Henry 1991). Near NGC 1399 ($b = -54°$), we obtained μ_λ(152 nm) $\gtrsim$ 23.3 mag arcsec^{-2} and μ_λ(249 nm) $\gtrsim$ 25.0 mag arcsec^{-2} before correction for residual plate fog.

Photometry was obtained in circular annuli after individual point sources and artifacts were masked out. Photometric uncertainties were estimated from the standard error of the mean net flux based on pixel-to-pixel variations; they ignore sky background gradients but include the effects of real flux gradients within the finite apertures. The use of circular rather than elliptical annuli or inclined systems like M31 and M81 has the effect of averaging the flux over a range of intrinsic radii in each annulus and, hence, slightly reduces the amplitude of the derived color gradients.

3. RESULTS

The ellipticals and spiral bulges are extended in both the NUV and the FUV. They present a relatively smooth appearance both in the direct images and in $\mu(r)$ plots, with none of the clumpiness which is readily apparent in UV or optical images of disk galaxies with ongoing massive star formation. The NUV frames for the M32 field and the central bulge of M31 are reproduced in Figures 1 and 2 (Plates L26–L28). Although OB associations are easily recognizable in the disk of M31 on both NUV and FUV frames, few candidates for massive OB stars are present in the bulge. Figure 2*b* is a spatially filtered version of Figure 2*a*, which should emphasize UV point sources superposed on the bulge; no convincing cases are present. The limiting magnitude for detection of point sources at a distance of ~30" from the M31 nucleus is m_λ(245 nm) ~ 18.4, which corresponds to M_λ(249 nm) ~ −6.4. Individual stars hotter than B1 V or B8 Iab would be brighter than this threshold, as would blended images of somewhat cooler objects. If the FUV light from the M31 bulge originated in recently formed massive stars with a normal initial mass function, there would be ~200 OB stars brighter than this limit within $r \leq 2'$. The apparent magnitude detection threshold for the other three systems is similar.

We conclude that the UV brightness of these four systems is not produced by recent massive star formation. This is consistent with the earlier evidence discussed in § 1. It is also strongly corroborated by 90–180 nm spectra of NGC 1399 obtained simultaneously with the Hopkins UV Telescope during the *Astro-1* mission. The weakness of C IV (155 nm) and the continuum shape shortward of 120 nm in these spectra led Ferguson et al. (1992) to conclude that massive stars are not responsible for the FUV light and that among low-mass types, EHB stars are favored over PAGB stars because of their slightly lower temperatures ($T_e \lesssim$ 25,000 K).

Hubble Space Telescope (*HST*) imaging would be required to search for individual low-mass objects. Our photometry indicates that PAGB or PEAGB types would appear in the FUV at ~21–24 mag with a surface density of ~0.1–1 arcsec^{-2} within the inner 2' of M31's bulge.

There is no evidence that the nuclei of these objects are unusually bright in the UV, at least at our spatial resolution. In fact, for M31 and M81 the region within $r = 3''$ is brighter in the NUV, with respect to the core of the surrounding spheroidal component, than it is in the FUV. This produces the small central reddening in their color profiles (Fig. 4 below). In M31 the central NUV brightness profile parallels that in the *R*-band derived by Kent (1987), when smoothed to the UIT resolution, while the FUV profile is less centrally peaked. The nuclear dust patch found by Kent (1983) in M31's bulge could be responsible for part or all of the difference. M81 is known to contain a low-level active nucleus (Filippenko & Sargent 1988), and there is some evidence from *IUE* spectra that the nucleus is bluer in the UV than the inner bulge (Reichert et al. 1992). However, our FUV profile for M81 is smoothly continuous for $r < 5''$ and does not exhibit the nuclear peak present in the NUV frames of M81 and M31. The point-spread functions (PSFs) of the two frames seem reasonably well matched, though only faint comparison stars are present on the FUV frames. These results suggest that the compact nuclear populations may contain less prominent UVX components than the immediately surrounding bulge population. UV/optical imaging with the *HST* FOC could quickly check them.

The mean surface brightness profiles for all four systems are smooth to levels near or below the sky background. In both the NUV and FUV, they follow a de Vaucouleurs profile ($\mu \sim a + br^{0.25}$) reasonably well, with only small deviations of the kind previously found at optical wavelengths. For M31, our NUV profile agrees well with the mean of the major- and minor-axis *R*-band profiles derived by Kent (1987) out to our last measured point at $r = 167''$. There is only a modest color trend, with m_λ(249 nm) − *R* changing from ~4.05 near the center to ~4.30 at large *r*. The profiles for NGC 1399 are shown in Figure 3. The center of this object is remarkably bright in the FUV, confirming the spectroscopy of Ferguson et

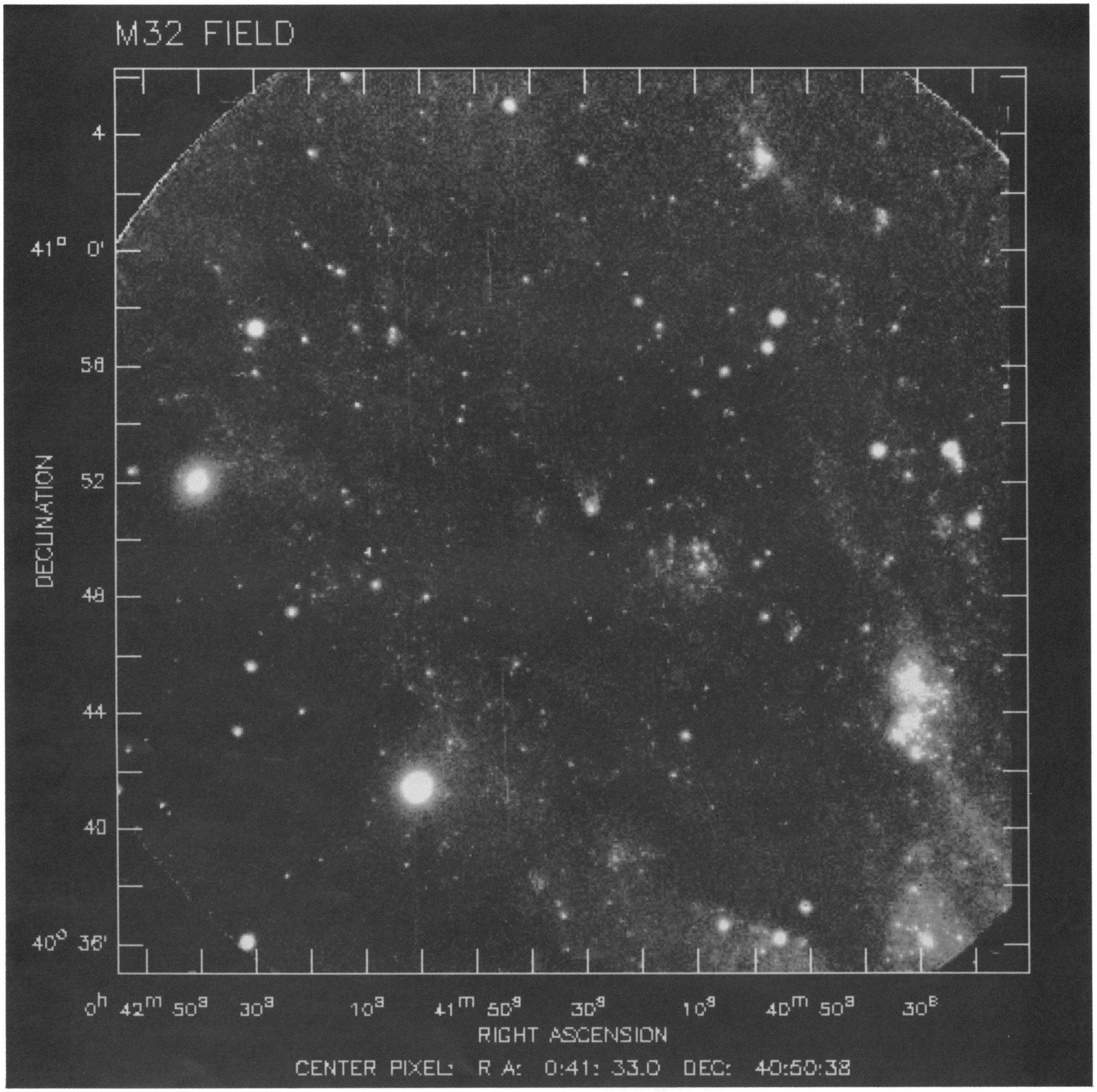

FIG. 1.—Near-ultraviolet (249 nm) UIT image of the southwestern disk of M31. Included are the elliptical galaxy M32 ($\alpha = 0^h42^m41^s$, $\delta = 40°52'$) and the OB association NGC 206 ($\alpha = 0^h40^m31^s$, $\delta = 40°44'$). The bright star at the lower left is the 7th magnitude F5 star HD 3914. The edge of the 40′ diameter UIT field is visible in the corners. A faint OB association in M31's disk is just northwest of M32; this region was masked out of the image before performing photometry on M32. Coordinates are for equinox 2000.

O'CONNELL et al. (see 395, L46)

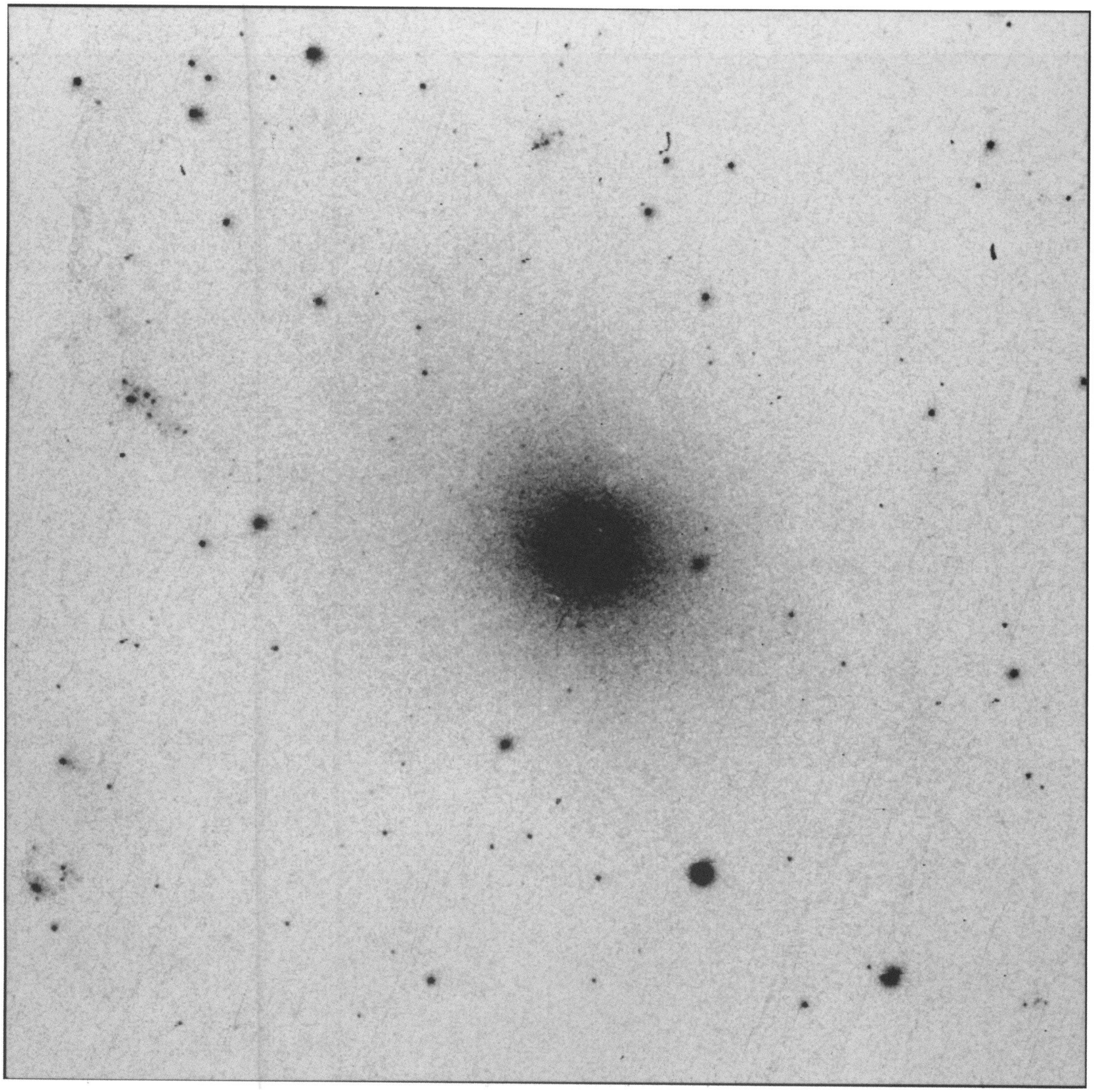

FIG. 2a

FIG. 2.—(a) Near-ultraviolet (249 nm) UIT image of the center of M31. The frame is 19'.4 on a side; north is at top and east is to the left. Several conspicuous OB associations are visible to the north and east of the bulge, but the bulge does not resolve into such objects. (b) Spatially filtered image of the center of M31 in which the image in (a) has been shifted by 1 pixel and subtracted from itself. This emphasizes the high-frequency structure and allows stars to be isolated even against a bright background. There is no evidence of a significant massive OB star population in the central bulge. The small "depression" in the bulge just northwest of the nucleus is an artifact.

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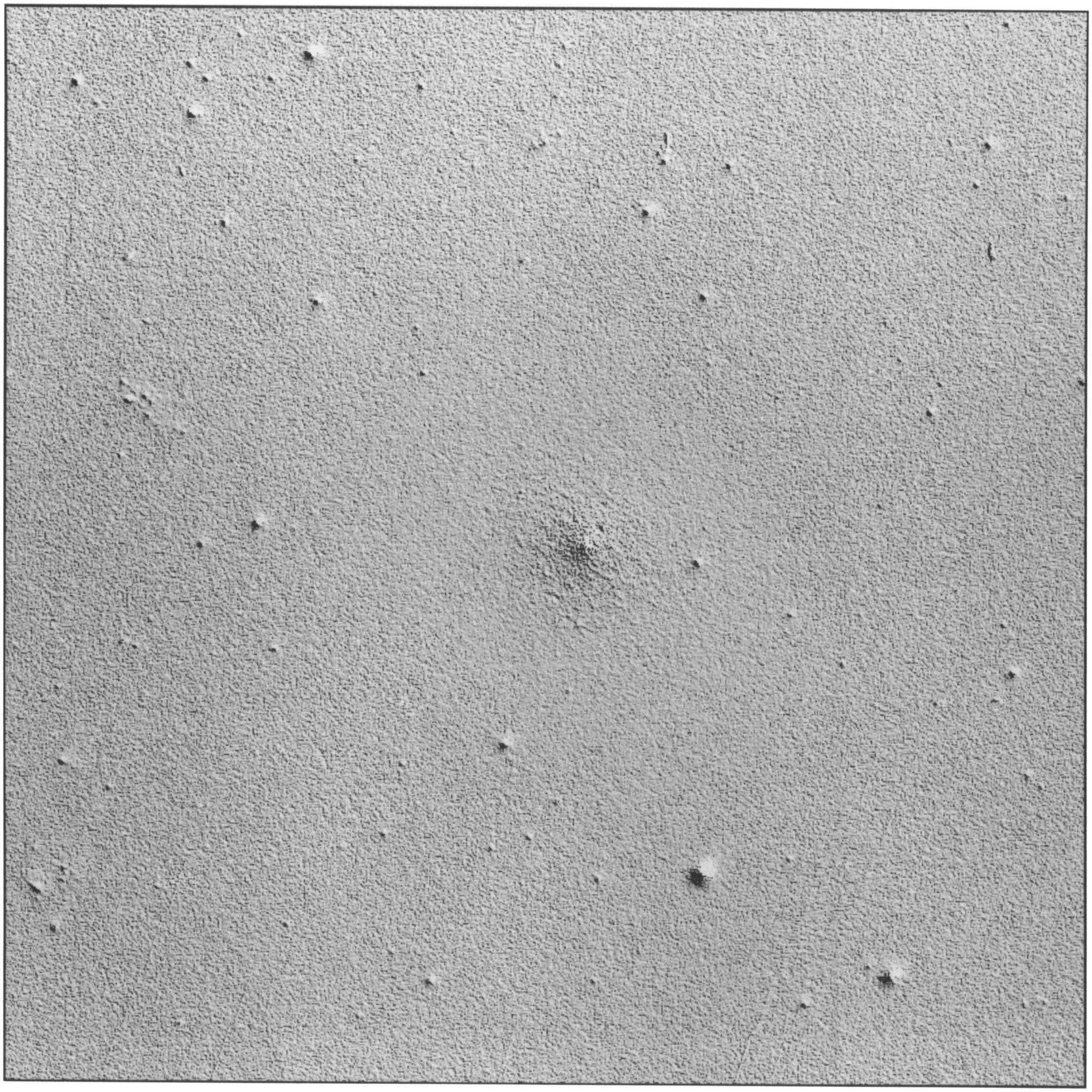

Fig. 2*b*

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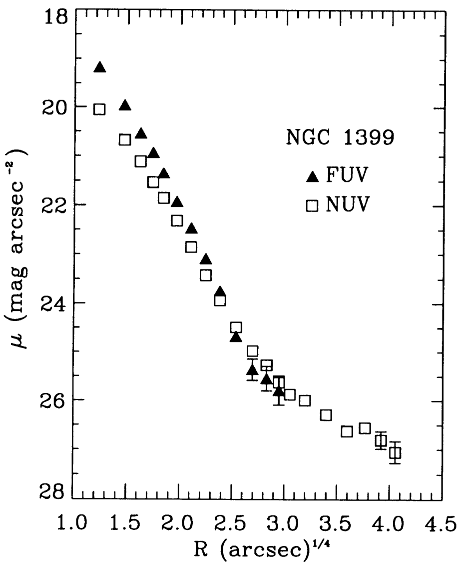

FIG. 3.—UV surface photometry for NGC 1399. The innermost point averages all pixels with $r < 3''.3$. Two sigma error bars are plotted only where they are larger than the symbols. The difference in slope between the NUV (249 nm) and FUV (152 nm) curves represents a large color gradient.

al. (1992) and Burstein et al. (1988). However, the FUV brightness profile is steeper than the NUV, such that the center is bluer in UV colors than the exterior. There is a flattening of the NGC 1399 isophotes for $r \lesssim 5''$ in both the NUV and FUV frames, which we believe is real. Structure of this type has not been reported at longer wavelengths (Mackie, Visvanathan, & Carter 1990; Bicknell et al. 1989). Again, higher resolution UV imaging is desirable.

UV colors, defined as $(152 - 249) \equiv m_\lambda(152 \text{ nm}) - m_\lambda(249 \text{ nm})$, are plotted as a function of radius in Figure 4 for all four objects. Our colors for the central 10″ of M31 and M32 are only 0.06 and 0.04 mag redder, respectively, than those derived from the Burstein et al. (1988) *IUE* spectra. Neither of the other objects had full *IUE* coverage in the Burstein et al. sample. We have not made foreground extinction corrections to the colors. These would be small or zero for NGC 1399 and M81; for M31 and M32 they would be $\delta(152 - 249) \sim 1.7E(B-V) \sim 0.17$, which is small compared with the total color range in the figure.

There are two striking aspects of Figure 4. First, there are gross differences, of up to 3 mag, in the nuclear (152−249) colors of the four systems. NGC 1399, the most luminous and metal-rich galaxy, is the bluest object, while M32, the least luminous, is the reddest. The color separation is consistent with earlier results from *IUE*, as summarized by Burstein et al. (1988). Second, all four systems exhibit strong radial gradients in UV color, with amplitudes of up to ∼1 mag. The gradients are smooth from the centers outward. In the three most luminous objects, the color becomes redder with increasing radius; in M32 it becomes bluer. It is noteworthy that NGC 1399, M31, and M81 all have comparable color gradients, which are independent of the galaxies' distances to first order in the variables plotted (magnitudes versus log radius).

This behavior in the UV is dramatically different than in the optical/IR, where old populations typically exhibit remarkable homogeneity (a range of central color of ∼0.1 mag) and only mild color gradients. More luminous systems are slightly redder in optical colors, and most objects become slightly bluer at larger radii (e.g., Faber 1977; Peletier et al. 1990). These effects are interpreted to reflect the mean metal abundance of the population, which increases with a galaxy's luminosity and decreases with radius within a given galaxy. Note that the UV behavior is opposite to the optical in both luminosity and radial dependence.

4. DISCUSSION

The UIT photometry provides the first strong evidence for extended color gradients of large amplitude in old stellar systems. We believe the UV gradients represent real changes in the stellar populations with radius. Experiments show that our colors for the inner 30″ of these objects are not very sensitive to the adopted sky backgrounds or density-to-intensity calibrations. As noted, where our photometry can be compared with earlier ground-based and UV observations, it agrees well. There was preliminary evidence in earlier UV studies for color gradients in M31 and Virgo ellipticals (e.g., Deharveng et al. 1982; Welch 1982; Kodaira et al. 1990). In particular, Welch (1982) found a UV gradient for M31 from *IUE* spectra which is comparable to ours over the inner 6″. The smooth trends with radius rule out nuclear activity as the source of the color changes. Finally, extinction by internal dust is unlikely to play a large role. Large values of $\delta E(B-V)$, ∼0.5 mag, would be required to produce the observed color changes. Also, the color gradients are similar in the two Sb spirals and in the gE NGC 1399, which probably differ considerably in central dust content.

For the objects other than M32, the photometry is consistent with a hot UVX component which is more strongly concentrated to the center of the galaxy than the bulk of the old

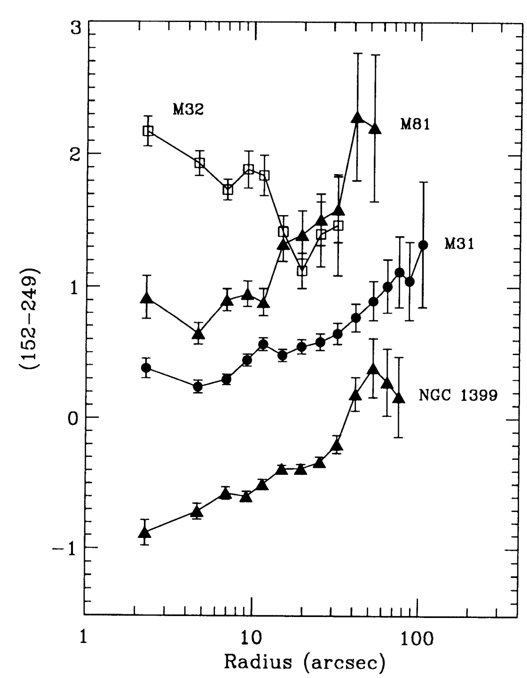

FIG. 4.—Comparison of the (152−249) colors in annular apertures for the four objects in the sample. The plots are truncated where the photometry becomes unreliable. The innermost point averages all pixels with $r < 3''.3$. Two sigma error bars are plotted. For orientation, the (152 − 249) colors of normal O7, B2, B5, A0, and A5 main-sequence stars would be −1.3, −1.1, −0.8, +0.1, and +2.2, respectively.

population. If metal abundances decline outward, the sense of the correlation is the same as the overall UVX/abundance correlation found for galaxy centers by Burstein et al. (1988). The simplest explanation, then, is that the UVX is responding to metal abundance differences within, as well as between, galaxies. This response appears to be far stronger than the blanketing and isochrone effects apparent at optical/IR wavelengths, implying that UV photometry may be a powerful means of tracing metal abundance trends in old populations.

However, there is nothing in our observations which rules out the influence of other parameters. As noted in the introduction, age (or, equivalently, mass at the base of the giant branch) is also expected to affect the net UV luminosity of a population. In fact, there is preliminary evidence that parameters other than abundance are involved. The UVX seems stronger in "boxy" than in "disky" E galaxies (Longo et al. 1989), and S0 galaxies have a steeper NUV color-luminosity relation than do E galaxies (Smith & Cornett 1982; Kodaira et al. 1990). Further, the correlations of Burstein et al. (1988) show that the UVX has a large range at constant Mg_2 in luminous objects. If abundance alone controls the UVX, then Figure 4 predicts that the metallicity for the outermost measured point in NGC 1399 is higher than that in the core of M31. This can be tested spectroscopically.

Our preliminary conclusion that the nuclear populations of M31 and M81 are not quite as blue as the inner bulges suggests that the nuclei may have somewhat different compositions and/or ages. Higher resolution images with *HST* and a good map of the nuclear dust distributions would be useful.

The UV color gradient for the Local Group E galaxy M32 is opposite to the other systems. The photometry is less good in this instance, since the galaxy is faint in the FUV and is superposed on the outer disk of M31. Although we rejected all resolved objects and those regions most likely to suffer disk contamination, M32's colors for $r > 30''$ are not well determined. A conservative statement is that a positive color gradient of the size seen in the other objects is excluded for M32 by our photometry. Because M32 has the lowest luminosity and mean metal abundance of the objects studied, its behavior could reflect a phase transition in the dominant type of UVX star (Greggio & Renzini 1990). Alternatively, the absence of a positive color gradient could be related to the fact that it appears to contain a significant intermediate-age ($\sim$5 Gyr old) population (O'Connell 1980; Freedman 1992; Davidge & Nieto 1992).

Hundreds of people contributed to the success of the *Astro-1* mission and the UIT experiment, and we gratefully acknowledge them collectively here. We also thank Harry Ferguson for communicating the HUT spectroscopic results in advance of publication, and Steve Kent for helpful comments. This research was supported in part by NASA grants NAG 5-700 and NAGW-2596 to the University of Virginia.

REFERENCES

Bertola, F., Capaccioli, M., & Oke, J. B. 1982, ApJ, 254, 494
Bicknell, G. V., Carter, D., Killeen, N. E. B., & Bruce, T. E. G. 1989, ApJ, 336, 639
Bohlin, R. C., Cornett, R. H., Hill, J. K., Hill, R. S., O'Connell, R. W., & Stecher, T. P. 1985, ApJ, 298, L37
Burstein, D., Bertola, F., Buson, L. M., Faber, S. M., & Lauer, T. R. 1988, ApJ, 328, 440
Code, A. D. 1969, PASP, 81, 475
Code, A. D., & Welch, G. A. 1979, ApJ, 228, 95
Davidge, T. J., & Nieto, J.-L. 1992, ApJ, 391, L13
Deharveng, J. M., Joubert, M., Monnet, G., & Donas, J. 1982, A&A, 106, 16
Faber, S. M. 1977, in Evolution of Galaxies and Stellar Populations, ed. B. M. Tinsley & R. B. Larson (New Haven: Yale Univ. Obs.), 157
Ferguson, H. C., et al. 1992, ApJ, in press
Filippenko, A. V., & Sargent, W. L. W. 1988, ApJ, 324, 134
Freedman, W. L. 1992, in IAU Symp. 149, The Stellar Populations of Galaxies, ed. A. Renzini & B. Barbuy, in press
Greggio, L., & Renzini, A. 1990, ApJ, 364, 35
Henry, R. C. 1991, ARA&A, 29, 89
Hills, J. G. 1971, A&A, 12, 1
Kent, S. M. 1983, ApJ, 266, 562
Kent, S. M. 1987, AJ, 94, 306
Kodaira, K., Watanabe, T., Onaka, T., & Tanaka, W. 1990, ApJ, 363, 422
Longo, G., Capaccioli, M., Bender, R., & Busarello, G. 1989, A&A, 225, L17
Mackie, G., Visvanathan, N., & Carter, D. 1990, ApJS, 73, 637
Mathews, W. G. 1990, ApJ, 354, 468
Norgaard-Nielsen, H. U., & Kjægaard, P. 1981, A&A, 93, 290
O'Connell, R. W. 1980, ApJ, 236, 430
O'Connell, R. W., Thuan, T. X., & Puschell, J. J. 1986, ApJ, 303, L37
Oke, J. B., Bertola, F., & Capaccioli, M. 1981, ApJ, 243, 453
Peletier, R. F., Davies, R. L., Illingworth, G., Davies, L., & Cawson, M. 1990, AJ, 100, 1091
Reichert, G. A., Puchnarewicz, E. M., Filippenko, A. V., Mason, K. O., Branduardi-Ramont, G., & Wu, C.-C. 1992, preprint
Schönberner, D. 1983, ApJ, 272, 708
Smith, A. M., & Cornett, R. H. 1982, ApJ, 320, 609
Stecher, T. P., et al. 1992, ApJ, 395, L1
Tinsley, B. M. 1972, in The Scientific Results from the Orbiting Astronomical Observatory (*OAP-2*), ed. A. D. Code (NASA SP-310), 575
Welch, G. A. 1982, ApJ, 259, 77
Wu, C.-C., Faber, S. M., Gallagher, J. S., Peck, M., & Tinsley, B. M. 1980, ApJ, 237, 290