We have imaged the nucleus of M32 at 1600 Å (FUV) and 5500 Å (V) using the Wide-Field/Planetary Camera 2 (WFPC2) aboard HST. We detected the nucleus at 1600 Å using the redleak-free Woods filter on WFPC2. The FUV light profile can be fit with a Gaussian of FWHM 0.46′′ (4.6 pixels), but cannot be resolved into individual stars; no UV-bright nuclear structure was detected. The (FUV−V) color of the nucleus is 4.9 ±0.3, consistent with earlier observations. We are unable to confirm any radial variation in (FUV−V) within 0.8″ of the nucleus; beyond that radius the FUV surface brightness drops below our detection threshold. We also performed surface photometry in V and found our results to be in excellent agreement with deconvolved, WFPC1 results. M32’s light profile continues to rise in a nuclear cusp even within 0.1 of its center. No intermediate-age stellar population is required by evolutionary population synthesis models to reproduce the (FUV−V) color of the nucleus, although these data and current models are insufficient to resolve this issue.

Subject headings: galaxies: individual (M32) — galaxies: nuclei — galaxies: stellar content — ultraviolet: stars

1. Introduction

At a distance of just 725 kpc, M32 is the nearest “true elliptical” (as contrasted to a dwarf elliptical\(^1\)) galaxy to the Milky Way. M32’s relative proximity allowed its outer regions to be resolved into stars by the first generation of large optical telescopes (Baade 1944), while its crowded inner regions remained unresolved until the advent of the Hubble Space Telescope (see Grillmair et al. 1996). The ability to study both the integrated light of M32 and the individual stars contributing to that light has made this galaxy a keystone of efforts to understand the stellar populations of elliptical galaxies beyond the Local Group.

One of the outstanding puzzles in the study of elliptical galaxies has been that of the ultraviolet excess (UVX); this term refers to the increase in flux shortward of 2000 Å seen in integrated spectra of elliptical galaxies, relative to the amount predicted by the simplest model fits to their optical spectra (Code 1969, Code & Welch 1979). An important step in identifying the stellar population responsible for the UVX was made by Burstein et al. (1988), who identified a strong correlation between the strength of the UVX and the mean metallicity of the galaxy in a sample of 24 quiescent systems.

M32 defined the UV-faint, low-metallicity end of the Burstein et al. (1988) sample, with an \(M_{1550} - V\)-band color of 4.5 ±0.2 and a mean metallicity of \([\text{Fe}/\text{H}] \approx -0.25\) (c.f. the discussion in Grillmair et al. 1996). Burstein et al. (1988) attributed the \((1550 - V)\) color of M32 to the presence of “classical” post-asymptotic giant branch (P-AGB) stars in the galaxy.

The ability of P-AGB stars to produce the \((\text{FUV} - V)\) color of M32 depends strongly on the age and metallicity distributions of M32’s stellar population. However, the very strong degree of central concentration which makes M32 an attractive target for studies of integrated light has hindered progress in the characterization of its stellar populations. Da Costa (1997) provides an overview of the various strands of evidence for and against the presence of an intermediate-age (few Gyr) population in M32.

Spectral syntheses performed by O’Connell (1980) indicated that the dominant contributors to the present-day optical luminosity of M32 are aged \(\approx 5\) Gyr with solar metallicity, but noted that the peak star formation rate might have occurred as long ago as 15 Gyr if the metallicity ranged as low as one-tenth solar. The existence of a major intermediate-age population in M32 has yet to be proven beyond a reasonable doubt despite the significant body of work dealing with this problem over the past two decades.

Ground-based (e.g., Freedman 1989, Davidge & Jones 1992) and HST (Grillmair et al. 1996) photometry have both been interpreted to indicate the presence of a significant metallicity spread in M32, in good agreement with recent long-slit spectra (Hardy et al. 1994). Most investigators seem to agree that significant numbers of stars with metallicities between \(-1.5 \leq [\text{Fe}/\text{H}] \leq 0.0\) are present in M32’s stellar mix; of course, the relative numbers of metal-rich and metal-poor stars are poorly constrained due to the usual age-metallicity tradeoff. Hardy et al. (1994) discovered the presence of a radial metallicity gradient: between 15” and 1′ from the galaxy’s center, the metallicity decreases at the rate \(\Delta[\text{Fe}/\text{H}] / \Delta\log(r) = -0.25 \pm 0.07\). An age gradient has also been reported for M32, as Grillmair et al. 1996 infer from the integrated line indices obtained by González (1993) that the nucleus of M32 is both several gigayears younger and somewhat more metal-rich than its outer regions. The deepest optical photometry of resolved stars (Grillmair et al. 1996) suggests a median age of 8 Gyr for M32 with an average metallicity of \([\text{Fe}/\text{H}] = -0.25\) for a region 1′–2′ from the nucleus.

M32 was observed by Bertola et al. (1995) in the far-ultraviolet using HST’s Faint Object Camera

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\(^1\)see Da Costa (1997) for some illumination of the murky waters of galaxian semantics.
(FOC), but there was difficulty in calibrating the absolute throughput of their filter set; M32’s FUV color was interpreted as an indication of a stellar population as young as 3 Gyr with slightly sub-solar metallicity. Brown et al. (1997) also imaged M32’s central region with FOC, using the F175W and F275W filters; their results seemed to indicate a conflict with stellar evolutionary theory, but the interpretation of the data was complicated by the redleak of the FOC ultraviolet filters (see, e.g., the discussion by Chiosi et al. 1997). M32 was also observed by the Ultraviolet Imaging Telescope (Ohl et al. 1997); a strong FUV−B color gradient was found, demonstrating that the galaxy’s UVX is weakest in the center and increases with radius.

We observed M32 as part of a WFPC2 GTO program to study the hot, luminous post-AGB populations and the UV upturn phenomenon in nearby early-type galaxies (Trauger et al. (1994b)). The use of the F160BW filter with WFPC2 provides a unique constraint on the FUV properties of M32, coupling HST’s high resolution (angular scales ≈ 0.′1 pix−1) with a zero-redleak (optical transmission ≪ 1% T max) wide-band filter that permits an accurate determination of the (FUV−V) color (c.f. Watson et al. 1994, Jones et al. 1996).

2. The Data: Observations, Reductions, and Photometry

Images of M32 were taken on 1994 October 19–20, with the nucleus imaged onto the WF3 chip of WFPC2. The data comprised 2 × 2000 sec exposures in F160BW (each exposure was split into two parts to facilitate cosmic ray rejection), together with a 10 sec and a 100 sec exposure in F555W. F160BW has a response from roughly 1200–2100 Å and is characterized by an extremely low throughput, while F555W is the WFPC2 analog to Johnson V. WFPC2 and its filter set are described in detail in Trauger et al. (1994a) and Biretta et al. (1996). The images were reduced in the standard way according to the procedures of Holtzman et al. (1995a); cosmic ray rejection and image manipulations were performed within IRAF2.

We identified bright stars in the outer regions of the nearby spiral M31 in the V and FUV frames and used their relative offsets to check the alignment of our WFPC2 images, which proved to be aligned at the sub-pixel level. The central 15′′ × 15′′ of M32, as seen at 1600 Å, are shown in Fig. 1; the galaxy is lurking in the shadows of detectability. A radial ultraviolet light profile, derived with the IRAF task IMEXAM, is shown in the upper left. The broad, shallow profile differs strongly from the high-amplitude peaks produced by the unremovable residue of large cosmic ray events such as the one several arcseconds East of the galactic nucleus. In contrast, application of IMEXAM to random locations in the field typically produced constant value or linear fits with no central peak.

Photometry was performed according to the procedure laid out in Holtzman et al. (1995b), using an 0′′5 aperture and their tabulated zeropoints for the STMAG system. Zeropoint corrections were made to account for the deposition of solid contaminants on the cold window of the CCD and for chip-to-chip variations in sensitivity, following Holtzman et al. (1995b). Burstein et al. (1988) report an interstellar reddening of A B = 0.31 mag towards M32; to correct for this, we assumed a standard Galactic extinction law with R V = 3.1 (Cardelli et al. 1989). A 555 was then taken from Holtzman et al. (1995b) to be 0.25 mag (assuming a K5 stellar spectrum). The selective extinction in F160BW was calculated using the method of Cole et al. (1997) to be A 160 = 0.70 mag for M32.

2IRAF is distributed by the National Optical Astronomical Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
3. The UV Color of the Nucleus

An automated search for point sources near the nucleus of M32 proved negative; visual inspection of the nuclear region suggested the presence of a faint, diffuse contribution to the FUV light. This impression was strengthened when we found that the best Gaussian fit to the diffuse light peaked at the position of the optical center of the galaxy, with a FWHM = 4.6 pix (compare to the F160BW point-spread function with FWHM ≈ 2.1 pix). For display purposes, we convolved the F160BW image with a 5×5 median filter in order to sharpen the contrast between diffuse features and the background. The filtered image is shown in Fig. 2; we have plotted isophotes of the F555W image on top of the F160BW image in order to demonstrate that the emission we have identified with the nucleus is indeed coincident with the optical center of the galaxy.

Aperture photometry of the nucleus yielded \( m_{160} = 18.39 \pm 0.26 \) mag (1σ random photometric error; systematic effects are expected to create an additional ≈10% uncertainty). To quantify the significance of this measurement, we placed 120 identical 0\′.5 apertures at random across the combined WF3 frame and examined the results. Sky values were determined locally in all cases, and the mean value was not found to vary appreciably across the field. The resulting photometry showed that M32’s nucleus is the brightest region of the WF3 frame. A comparison to the distribution of test aperture magnitudes showed that the nucleus sits 3.9σ above the background, defined by the mean number of counts in the test apertures and the scatter around that mean. This number is likely an underestimate of the significance of the detection, because the mean of the test aperture counts was not corrected for contamination by unremoved cosmic ray events. We determine from the test aperture count distribution that our minimum 3σ detection level occurs at \( m_{160} = 18.7 \).

In contrast, the nucleus is extremely obvious in the V-band; the diffuse optical light has an azimuthally averaged FWHM of 4.2 pix, and a total magnitude \( m_{555} = 12.99 \pm 0.01 \). Thus we find a dereddeded (160−555) color of 4.9 ± 0.3 for the nucleus of M32. This is consistent with the preliminary analysis of the same dataset by Jones et al. 1996 which yielded (160−555) = 4.7 ± 0.2, and in satisfactory agreement with the IUE (1550−V) color of 4.50 reported by Burstein et al. (1988). Varying the aperture radius between 0\′.1 and 0\′.8 uncovered no variation in (160−555), although the errors are large enough to hide a mild gradient if it exists. Beyond 0\′.8, the FUV surface brightness drops below our detection threshold.

4. Surface Photometry of the Nuclear Region

We performed surface photometry within 5\″ of the nucleus in the F555W frames. Our results agree with the WFPC1 results of Lauer et al. (1992). We find a surface brightness at 0\″3 of \( \Sigma_{555} = 12.5 \) mag arcsec\(^{-2}\), rising to 11.9 mag arcsec\(^{-2}\) at 0\″1, in excellent agreement with both Lauer et al. (1992) and the model mass distribution derived by van der Marel et al. (1997a,b). The F555W major axis radial profile of the central 5\″ of M32 is shown in Figure 3. M32 shows a pronounced nuclear cusp in its light profile.

We did not obtain sufficient signal-to-noise in F160BW to perform accurate surface photometry, but the FUV light of M32’s nucleus is clearly more broadly distributed than a point source. We infer from our agreement with the IUE (1550−V) color the the FUV light is distributed similarly to the optical light. The smoothly distributed light indicates that it is likely due to the presence of a relatively large number of faint objects.
5. Discussion

It seems impossible to reproduce the integrated spectrum of M32 with a single-age, single-metallicity “simple stellar population” (SSP) (Hardy et al. 1994). However, SSPs remain a useful tool for interpreting the (160−555) color, because they provide the tools with which to construct more realistic models. For SSPs, the (FUV−V) color is predicted to be a sensitive function of both age and metallicity, and hence a valuable observation for the derivation of star formation histories (Bressan et al. 1994). The exact dependencies of (FUV−V) on stellar age and metallicity are highly uncertain, and this limits its predictive power. As discussed in detail by Yi et al. (1997), the age predictions depend critically on poorly modeled processes such as stellar mass-loss. Therefore, the uncertainties in our interpretation are dominated by systematic model effects rather than observational errors.

In order to provide an interpretational starting point, we compared the observed (160−555) color of the nucleus of M32 to the SSP predictions of Tantalo et al. (1996). Table 1 gives the ages of SSPs which are predicted to exhibit (160−555) = 4.9 ±0.3, for a range of metallicities. In Table 1, t_y indicates the acceptable age range for models in which the FUV light derives from main-sequence stars, while t_o gives the ages for which evolved stars provide the FUV light. The errorbars in Table 1 are internal, random, observational errors only, and merely reflect the propagation of photometric error into the model predictions. A thorough discussion of the systematic errors in these models is beyond the scope of this paper (c.f., Yi et al. 1998), but uncertainties in the physics of stellar-mass loss and helium-enrichment limit the absolute precision of such models to several billion years (particularly the older models, which most concern us here). The ages in Table 1 are therefore most useful as relative measures, so that M32’s stellar populations may be compared with those of other galaxies using a consistent set of models. As absolute measures, they are subject to extreme uncertainty.

In these models, the ratio of FUV to optical light is not a monotonically decreasing function of age: early in a galaxy’s lifetime, (FUV−V) increases (gets redder) as the hot upper main-sequence stars die off. Eventually, as the total luminosity of the SSP continues to fade with age, the FUV contribution of the short-lived P-AGB stars begins to become important, and (FUV−V) becomes bluer again. At sufficiently high metallicities (Z > 2Z⊙), these models predict a point at which low-mass helium-burning stars avoid the AGB in favor of long-lived UV-bright phases, causing a sharp increase in the FUV flux as this behavior sets in at ages ≈5–10 Gyr.

The (160−555) color of M32 can be matched by either young or old SSPs. We rule out the young (0.5–2 Gyr) class of models for two reasons: first, these ages are much younger than even the youngest intermediate-age populations inferred from optical spectroscopy and photometry of M32; and second, models of P-AGB stars (Vassiliadis & Wood 1994) for such young ages are predicted to have m_{160} ≈ 18.5 at the distance of M32; only one such P-AGB star would be required to account for the FUV light of M32’s nucleus, and would be seen as a point source in our images. The remaining models indicate an SSP age of 12–13 Gyr for M32’s nucleus for metallicities less than about 5 times solar. In this type of SSP, the FUV light is produced by classical P-AGB stars. In the super metal-rich case the age of the SSP drops to ≈6 Gyr due to the production of hot AGB-manqué stars via metal-enhanced mass loss on the RGB (Tantalo et al. 1996, Dorman et al. 1995, Greggio & Renzini 1990). It is important to remember that these age values are subject to large, model-driven systematic errors and should not be considered as definitive determinations.

M32 is not a likely candidate to harbor AGB-manqué stars, as the required metallicity is too high by a factor of two or more. The best matching SSPs of reasonable metallicities are then 12–13 Gyr old; this is consistent with the results of Grillmair et al. 1996 indicating that half the optical light of M32 comes from
stars older than \( \approx 8 \) Gyr. Note that M32 is not an SSP; any intermediate-age population that contributes to the optical light is predicted to be FUV-faint and thus pushes the required age of the FUV-bright population to even older ages in order to reproduce the integrated \((160−555)\) color.

We do not have enough radial coverage in F160BW to permit comparison with the UIT result that M32’s FUV light falls off more slowly with radius than its optical light (Ohl et al. 1997). No gradient in \((160−555)\) is seen with the central 0′′.8 of M32’s nucleus. If the UIT result is interpreted in the context of SSPs, it would suggest that either M32’s metallicity is increasing with radius (contrary to previous results of Hardy et al. 1994), or that the galaxy’s mean age is increasing with radius. This type of radial age gradient has also been suggested to exist in the dwarf elliptical galaxy NGC 147 (Han et al. 1997) and in the Andromeda I dwarf spheroidal (Da Costa et al. 1996); it may turn out to be a general feature of small, spheroidal galaxies.

6. Summary

• We have imaged the nucleus of M32, an elliptical galaxy with a weak ultraviolet upturn, in the visible and far-ultraviolet with WFPC2 aboard the Hubble Space Telescope. These data extend FUV observations of M32’s nucleus to smaller radii than have heretofore been possible. We found the nucleus to have a color \((160−555) = 4.9 \pm 0.3\), in agreement with the results from IUE.

• Like Bertola et al. (1995), we were unable to resolve the FUV light of M32 into individual stars. Unlike Bertola et al. (1995) and Brown et al. (1997), we do not require the presence of a 3–5 Gyr population or AGB-manqu’é stars to explain the \((FUV−V)\) color of M32. Using the simple stellar population models of Tantalo et al. (1996), we find that the \((160−555)\) color of M32 is most easily explained by the presence of a moderately metal-poor stellar population aged \( \geq 12 \) Gyr. Given the large uncertainties in the processes which can induce old, low-mass stars to high-temperatures, this age should be considered uncertain to within \( \pm \sim 5 \) Gyr (Yi et al. 1997, 1998); thus an intermediate-age population cannot be ruled out.

• Surface photometry in the visible is in excellent agreement with deconvolved WFPC1 and ground-based data (e.g., Lauer et al. (1992)). Because of the poor signal-to-noise ratio, there is no evidence in our data that the FUV light is distributed differently than the optical light.

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REFERENCES


Trauger, J.T., et al. 1994b, HST proposal, ID# 5630.
Table 1. Age ranges which reproduce the observed (160−555) color of the nucleus of M32, for five different metallicities. The colors are derived from the models of Tantalo et al. 1996. In the ‘young’ SSPs, the UV light is provided by the main-sequence, while the ‘old’ SSPs derive their UV colors from evolved stars. Errorbars derive from propagation of our photometric errors into the models; additional systematic errors of order ±5 Gyr (Yi et al. 1998) should be applied to the old SSP solutions (Column 3).

<table>
<thead>
<tr>
<th>Z</th>
<th>$t_y$ (Gyr)</th>
<th>$t_o$ (Gyr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.004</td>
<td>2.6 ±0.4</td>
<td>13.1 ±0.4</td>
</tr>
<tr>
<td>0.008</td>
<td>1.7 ±0.2</td>
<td>12.3 ±0.3</td>
</tr>
<tr>
<td>0.02</td>
<td>1.1 ±0.1</td>
<td>13.0 ±0.4</td>
</tr>
<tr>
<td>0.05</td>
<td>0.69 ±0.04</td>
<td>12.6 ±0.6</td>
</tr>
<tr>
<td>0.10</td>
<td>0.62 ±0.05</td>
<td>5.9 ±0.1</td>
</tr>
</tbody>
</table>
Fig. 1.— $15'' \times 15''$ of the $2 \times 2000$ sec F160BW image of M32, centered on the galaxy's nucleus as determined from the F555W images. North and East are indicated on the figure. The galaxy is not immediately obvious in the far-ultraviolet image, but proves to be detectable at the $3.9\sigma$ level. At upper left, we have plotted a fit to the radial profile of the nucleus (heavy dashed line); for comparison, a point-source profile has been scaled to the same total flux and overplotted on the data (narrow dashed line). Sharply peaked cosmic-ray residuals can be seen across the image (e.g., the dark region $5''$ E of the nucleus).
Fig. 2.— The F160BW image from Fig. 1, after median filtering to enhance the visibility of extended sources. In the median-filtered image, the nucleus has risen up out of the noise, and is seen to correspond exactly to the center of the galaxy. F555W isophotal contours are overplotted in black.
Fig. 3.— Major-axis radial profile of M32 as seen in the F555W filter. No deconvolution has been applied. The results are in excellent agreement with earlier determinations, and extend to within 0′′1 of M32’s center.