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ULTRAVIOLET IMAGING TELESCOPE PHOTOMETRY OF MASSIVE STARS: THE OB ASSOCIATION NGC 206 IN M31

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ABSTRACT

The Ultraviolet Imaging Telescope (UIT) obtained UV images of the giant M31 OB association NGC 206. Magnitudes in bands at 1520 and 2490 Å were obtained for 30 massive stars, which demonstrate the effectiveness of UIT for photometry of moderately crowded hot stars to $V \sim 21$. The UV colors and magnitudes observed for stars in NGC 206 place them in the region of the color-magnitude diagram occupied by evolutionary models for 30–60 $M_\odot$ stars, after correcting for extinction. The brighter stars are systematically redder than the fainter stars, indicating that they are supergiants of age $\sim$4 Myr, while the fainter, bluer stars are nearer age zero. The relative numbers of probable supergiants measured by us and the number of probable main-sequence O stars measured from optical images are in agreement with the relative lifetimes. Calculated UIT colors are presented for a library of standard star spectra constructed from *IUE* and ground-based observations.

Subject headings: galaxies: individual: M31 — ultraviolet: general

1. INTRODUCTION

Ultraviolet imagery of spiral galaxies is a sensitive probe of regions of active star formation, where the emission is dominated by luminous hot massive stars. NGC 206 is the most prominent such region in the nearby Sb galaxy M31. It was included on frames taken of M31 with the Ultraviolet Imaging Telescope (UIT) during the *Astro-1* Spacelab mission.

Visual-band photometry of individual stars in NGC 206 has been performed by several authors, including Massey, Armandroff, & Conti (1986, hereafter MAC) and Odewahn (1986). MAC measured 620 stars, estimating $E(B-V) = 0.12$ from a reddening vector technique in the $U-B$ versus $B-V$ diagram. Odewahn determined B-magnitudes and $B-V$ colors for 150 stars, and estimated a larger value, $E(B-V) = 0.27$, from the distribution of $B-V$ colors compared with color distribution models for young clusters.

Hutchings, Massey, & Bianchi (1987) observed MAC 277, one of the brightest stars in NGC 206, using *IUE*. They found the star to be unexpectedly red in the UV compared with Galactic O stars and concluded that the extinction was best described by $E(B-V) = 0.11$ in the Galaxy, with an additional $E(B-V) = 0.1$ in M31 with an extinction curve with enhanced LMC–like far-UV extinction (Fitzpatrick 1985). We have used this reddening model to deredden our observed fluxes and colors. The reddening corrections so determined, 1.61 mag for the A1 (near-UV) band, and 1.82 mag for the B1 (far-UV) band, are near the average of the corrections implied by the MAC and the Odewahn extinctions using the Galactic reddening curve.

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2. OBSERVATIONS AND DATA REDUCTION

A detailed description of the UIT instrument, including plots of the wavelength dependence of the bandpasses, may be found in Stecher et al. (1992). The wavelength centroids of the B1 and A1 bandpasses used in observing NGC 206 are 1520 and 2490 Å, with widths 354 and 1150 Å. Magnitudes in the two bands will be referred to as m_{152} and m_{249}, respectively. Three exposures of NGC 206 were obtained with each camera, with exposure times about 23, 117, and 583 s in each case. Figures 1 and 2 (Plates L18 and L19) show 3′ × 4′ subimages extracted from the longest near-UV and far-UV exposures, respectively. The 30 stars measured in the two bands are circled on the near-UV (A1) image, except for MAC 277, which is indicated by a box.

The data reduction process is discussed by Stecher et al. (1992). The absolute calibration is determined as the ratio of the flux [in ergs (cm^2 Å s)$^{-1}$] averaged over the UIT bandpasses from well-exposed *IUE* spectra of several stars imaged by UIT during the *Astro* mission, to the total image fluxes (in linearized pixel units) above the sky in a 15 pixel (17″) radius aperture. The aperture is large enough to contain all the stellar signal. The resulting calibration is estimated to be accurate to about 10%.

The Fanelli, O'Connell, & Thuan (1987) library of stellar far-ultraviolet and visual spectra for stars over a range of spectral types earlier than A5 was extended to include near-UV spectra also and used, together with UIT filter curves measured in the laboratory (Stecher et al. 1992), to compute $m_{152} - m_{249}$ and $m_{152} - V$ color indices for the same range of spectral types. The $m_{152} - V$ colors illustrate the effectiveness of ultraviolet images in isolating the hot star component of the stellar population. The computed colors are given in Table 1.

3. ANALYSIS

Stars were located in NGC 206, and aperture and point-spread function (PSF) fit photometry performed, using IDL implementations of DAOPHOT algorithms (Stetson 1987). We identified 30 bright, relatively uncrowded stellar sources on both the near-UV and far-UV images.

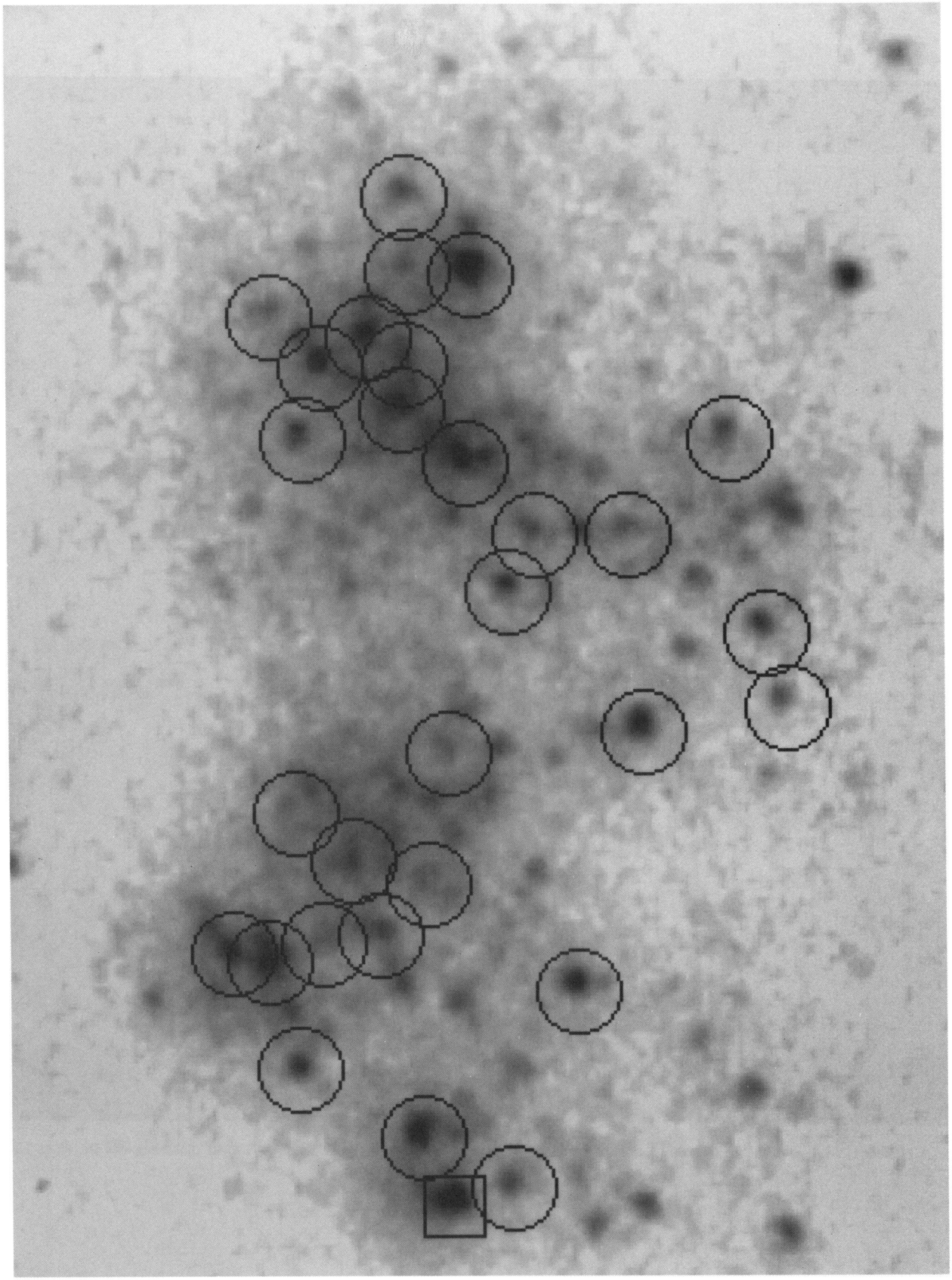

FIG. 1.—3′ × 4′ section of A1 (near-UV, 2500 Å) image, with north at top and east to the left. The 30 stars measured in both UIT bands are circled. MAC 277 is marked by a box.

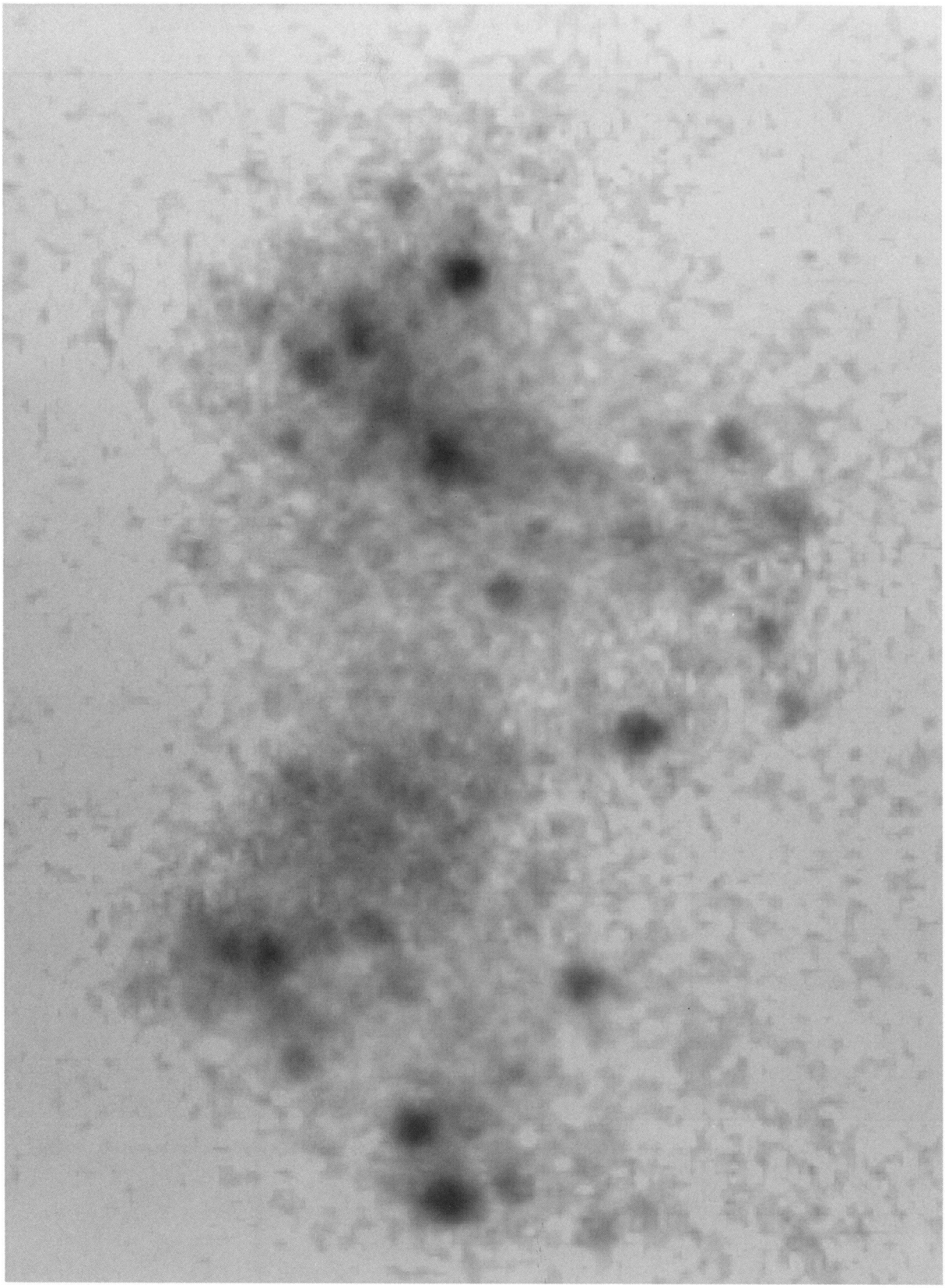

FIG. 2.—3′ × 4′ section of B1 (far-UV, 1520 Å) image, registered with Fig. 1

TABLE 1

COLORS IN UIT BANDS FOR MKS SPECTRAL TYPES

MKS	$m_{152}-m_{249}$	$m_{152}-V$
O3–O6 V	−1.32	−4.73
O7–B0 V	−1.30	−4.48
B1–B1.5 V	−1.28	−4.00
B2–B3 V	−1.12	−3.27
B4–B7 V	−0.95	−2.58
B8–B9.5 V	−0.67	−1.49
A0–A2 V	0.08	0.46
A5–A7 V	2.15	2.80
O5–O6 III	−1.32	−4.69
B0–B1.5 III	−1.18	−3.98
B3–B6 III	−0.98	−2.72
B7–B9 III	−0.60	−1.35
O9–B0.5 I	−0.99	−3.79
B3–B5 I	−0.54	−2.11
B8–A0 I	−0.20	−0.32

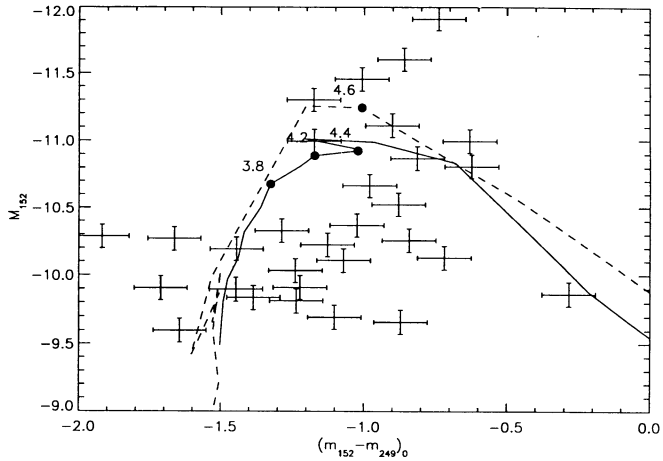

FIG. 3.—Ultraviolet color-magnitude diagram for the 30 stars measured by UIT, dereddened using the results of Hutchings, Massey, & Bianchi (1987), assuming a distance modulus of 24.19. The estimated photometric errors of 0.10 mag in M_{152} and 0.15 mag in $m_{152}-m_{249}$ are indicated by the error bars. The evolutionary track of a 40 $M_\odot$ star from the models of Maeder (1990) is shown as a solid line for younger ages, with age increasing as the star evolves to cooler temperatures. For larger ages the track is shown as a dashed line which evolves back to hotter temperatures. Solid circles with adjoining numbers indicate the positions of supergiants and ages in millions of years. MAC 277 is the second brightest star, with $M_{152} \sim -11.6$ and $m_{152}-m_{249} \sim -0.87$.

Aperture photometry was done using apertures of radius 3 pixels. PSF fit photometry was then done, with point-spread functions constructed for each bandpass from a few bright isolated stars which are not association members. These same stars were used to determine the aperture corrections necessary to correct the fluxes of the association members to a 15 pixel aperture, as used in determination of the absolute calibration. Magnitudes m_{152} are related to fluxes f_{152} by $m_{152} = -2.5 \log f_{152} - 21.1$. The aperture-corrected PSF fit values of m_{152} range from about 14 to 17. The faintest m_{152} of the 30 stars discussed here is ~ 17, corresponding to observed $V \sim 21$ for a hot star with the adopted reddening.

Humphreys, Massey, & Freedman (1990) have determined spectral types for five of the brightest early-type stars observed in NGC 206 by MAC, namely, MAC 277, MAC 231, MAC 485, MAC 478, and MAC 159. They have assigned spectral types B1 I, O8.5 If, B0 I, B0–B1 I, and B0 I, respectively. All of these stars were also observed by UIT. The $m_{152}-m_{249}$ colors obtained are −0.86, −1.02, −1.13, −0.81, and −0.98, after dereddening using the Hutchings et al. (1987) reddening model. These colors agree with the colors of stars of similar spectral types given in Table 1, within the estimated observational error of 0.15 mag.

Figure 3 is the $m_{152}-m_{249}$ versus M_{152} color-magnitude diagram for the 30 stars. The rms errors in relative magnitude are estimated at about 0.10 mag in M_{152} and 0.15 mag in $m_{152}-m_{249}$. The colors are dereddened using the Hutchings et al. (1987) reddening model for MAC 277, and a distance modulus of 24.19 is assumed. The UIT far-UV and near-UV magnitudes for MAC 277 are fainter than the magnitudes obtained by integrating the filter curves over the *IUE* spectra by 0.55 and 0.21 mag, respectively.

Several plausible causes for this level of disagreement exist. First, the comments entered by the *IUE* telescope operator on the spectra SWP 26492 and LWP 7021 indicate that both have very high background levels (155 and 175, respectively) and that the LWP spectrum is overexposed by a factor 1.5. Any nonlinearities in the *IUE* intensity transfer functions will be amplified in extracting a net spectrum when a large fraction of the gross spectrum is background. Last, the field contains several other stars within 20″ of MAC 277, possibly contributing to the measured spectra.

The evolutionary track for mass 40 $M_\odot$ (Maeder 1990), for ages 0 to ~ 5 Myr, is also plotted in Figure 3. Colors and magnitudes were computed using the model atmospheres of Kurucz (1991). Stars of mass 30 and 60 $M_\odot$ follow similar tracks, but brighter by ~ 1 mag for 60 $M_\odot$ and fainter by ~ 1 mag for 30 $M_\odot$.

For all three masses, the Maeder models begin with colors ~ -1.5, become brighter with slightly redder color for ~ 3 Myr, then loop redward to such low temperatures that they have little UV flux. This phase is shown as a solid line in Figure 3. The models return very briefly to near the main-sequence position at age ~ 5 Myr, as indicated by the dashed line in Figure 3. The range of the observed M_{152} magnitudes of stars in NGC 206 is consistent with the predictions of models, together with the adopted reddening and distance modulus. The range in observed color is about 1.0 mag, likewise consistent with the range spanned by the models. The brightest stars (including MAC 277) are systematically redder than the fainter stars, suggesting that they are supergiants of age ~ 4 Myr, while M_{152} suggests an initial mass about 60 $M_\odot$. Most of the stars plotted at $m_{152}-m_{249} \sim -1$ and $m_{152} \sim -10.0$ appear to be $M \sim 30$ $M_\odot$ supergiants at an age of ~ 3–4 Myr.

According to the evolutionary models of Maeder (1990), approximately 15%–20% of the lifetime of these massive stars is spent near the brightest magnitudes with colors redder than the main sequence. Since we have detected and measured ~ 20 probable supergiants here, we infer the existence of about 100 main-sequence precursors. Fainter stars are detectable on the UIT images, but crowding makes the photometry less reliable, so they are not included here. Roughly consistent with our expectations, MAC measured 118 stars in NGC 206 with M_V brighter than −4.0 and $(B-V)_0$ less than −0.30, where we have dereddened the MAC magnitudes and colors using the Hutchings et al. (1987) reddening model. Stars of this magnitude and color are probably O stars (Garmany 1990).

The total UV fluxes of NGC 206 above sky from the regions shown in Figures 1 and 2 are $f_{152} = 2.6 \times 10^{-13}$ ergs (cm^2 Å

s)$^{-1}$ and $f_{249} = 1.3 \times 10^{-13}$ ergs (cm^2 Å s)$^{-1}$. The 30 stars discussed here contribute ~ 0.29 of the flux in each bandpass.

UIT images have proved to be very effective for the photometry of massive stars in the Local Group. More extensive studies using images acquired during the *Astro* mission of M31 associations and several LMC regions are planned.

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