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IMAGES IN THE ROCKET ULTRAVIOLET: THE STELLAR POPULATION IN THE CENTRAL BULGE OF M31

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ABSTRACT

We discuss imagery of the bulge of M31 obtained with a rocket-borne telescope in two broad bands centered at 1460 Å and 2380 Å. The UV spatial profiles over a region ~ 200″ wide are identical with those at visible wavelengths. The absence of detectable point sources indicates that main-sequence stars hotter than B0 V are not present in the bulge. We suggest that the far-UV flux in old stellar populations originates in post–AGB stars. The UV flux from such stars is extremely sensitive to age and the physics of their previous mass loss.

Subject headings: galaxies: individual — galaxies: photometry — galaxies: stellar content — ultraviolet: general

I. INTRODUCTION

Ultraviolet imagery is an excellent means for investigating regions of active star formation, where the emission is dominated by luminous hot massive stars (Bohlin *et al.* 1982; Hill, Bohlin, and Stecher 1984). Observations of the globular cluster M5 have shown that populations of evolved low-mass stars in UV-bright evolutionary phases can also be studied effectively by means of rocket-UV imagery (Bohlin *et al.* 1983, 1985). The prominent Local Group SAb spiral M31 (NGC 224), containing both types of UV-emitting populations, was observed at 10″–20″ resolution by our ultraviolet imaging telescope on Astrobee flight 25.053 at 7:30 UT 1980 August 8.

Far-UV measurements of M31 were first reported by Code (1969) from *OAO 2* photometry in six bandpasses with a 10′ aperture. The upturn in the spectrum below 2000 Å has since been shown to be common in early-type systems (e.g., Oke, Bertola, and Capaccioli 1981), and it has been interpreted as arising either from newly formed massive stars (Tinsley 1972) or from hot evolved low-mass stars in the older population (Hills 1971; Faber 1983). This *Letter* reports the results of an investigation of the UV emission of the central bulge component, including an upper limit on the contribution of young main-sequence stars and an estimate of the contribution from horizontal-branch and hot post–AGB stars.

II. OBSERVATIONS

The payload consisted of a rocket-borne 31 cm f/5.6 Ritchey-Chrétien telescope with two microchannel plate image intensifiers coupled to IIa-0 film (see Bohlin *et al.* 1982). The two cameras had effective wavelengths for unreddened hot stars near 1460 Å (CsI cathode) and 2380 Å (CsTe cathode) with bandwidths 440 Å and 860 Å, respectively. The field of view was 80′ in diameter.

Images were obtained of two overlapping fields of M31, with the nucleus and surrounding bulge regions included in both. The flight data and associated laboratory calibration frames were digitized and reduced following the general procedure described by Bohlin *et al.* (1982).

The payload was destroyed when the parachute system failed, but the damaged film cassettes were recovered. Although most images suffered some degradation in the crash, data which were only slightly affected on the M31 bulge proved to be available in a 60 s CsI image (10A), and in the 25 s CsTe image (7B), which are the principal sources for the photometry reported in this paper. The absolute calibration was determined from the linearized and flat-fielded microdensitometry of the bulge region in these two images. The bandpass response functions of the two cameras were integrated over a spectrum interpolated from *ANS* fluxes of the same region (Wu *et al.* 1980). The absolute calibration was obtained by dividing the resulting fluxes by the sums of relative intensity units over a circular aperture of radius 85″ (equal in area to that of *ANS*). Similar treatment of short-exposure images gave absolute calibrations consistent with the longer exposures to within 3% for both cameras, thus verifying the linearity of the system.

Figure 1 (Plate L5) shows the two longest exposures of each field in each bandpass. The UV emission from M31 is dominated by the bulge and by a ring of OB associations,

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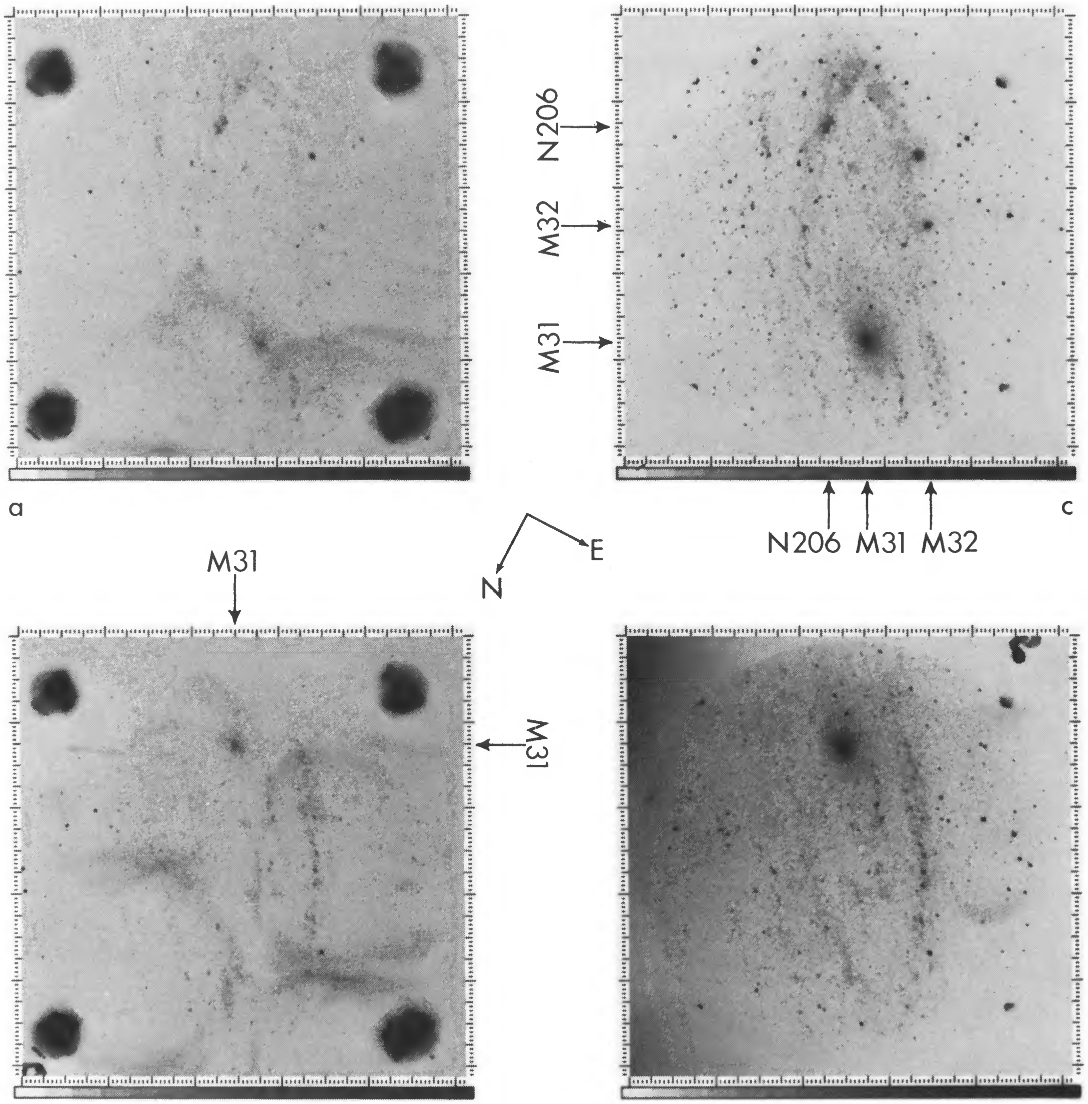

FIG. 1.—Images of M31 in two UV bandpasses overlapping 80′ fields, as follows: (*a*) image 6A: CsI 60 s exposure; (*b*) image 10A: CsI 60 s exposure; (*c*) image 7B: CsTe 25 s exposure; (*d*) image 15B: CsTe 20 s exposure. The position of the nucleus of M31 is indicated on both fields. The positions of M32 and the young cluster NGC 206 are shown for the images of the southern field (*a*) and (*c*). The major grid subdivisions correspond to 16′. Artifacts of the crash (see text) are most visible over the spiral arms of image 10A.

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corresponding to the H II regions cataloged by Baade and Arp (1964) and by Courtes *et al.* (1978).

III. DISCUSSION

The bulge region of M31 has a smoothly symmetric appearance in the UV; no significant internal structure is present. Figure 2 compares the minor- and major-axis profiles through the M31 nucleus in the CsI and the CsTe band with profiles derived from the 6500 Å band CCD image of Kent (1983), who kindly provided us with his data. The Kent data were smoothed to the resolution of the UV frames (21″ for the CsI band and 14″ for the CsTe band), and the extracted profiles were scaled to have the same average value over an area corresponding to the 2′.5 *ANS* satellite aperture. The plotted points are averages over areas the size of a resolution element, but spaced by half that amount.

Error bars for the UV data were determined from analysis of flat-field exposures taken during preflight calibration at densities near those in the M31 central bulge. In general, the intensity profiles in the three bandpasses are consistent within the 2 σ UV error bars. The exception is the CsI profile to the northeast of the nucleus, which is lower as a whole than that from the Kent 6500 Å data (see Fig. 2*c*). Probably this difference results from absorption by the dust features readily visible in both Kent's data and the atlas of Hodge (1981), although misregistration of the UV profile relative to the Kent profile by up to ~ 5″ is possible, given the noise level of the CsI data.

The similarity in spatial distribution illustrated here between the UV components and those which dominate at visible wavelengths is consistent with earlier *IUE* studies of spheroidal populations (e.g., Oke, Bertola, and Capaccioli 1981; Welch 1982; O'Connell, Puschell, and Thuan 1985), except that our images extend a factor of ~ 10 farther in radius. Mild color gradients reported within 10″ of the nucleus from *IUE* data (Welch 1982; Deharveng *et al.* 1982) could not be detected at the resolution and signal-to-noise ratio (S/N) of our data. We conclude that the UV emission from the inner bulge is dominated by the same old population (e.g., Spinrad and Taylor 1971) which dominates at visual wavelengths.

Localized regions of star formation are readily detectable in our UV images of the outer spiral arms of M31, but none are apparent in the inner bulge (see Fig. 1). Residuals between the two-dimensional UV images and the Kent data indicate that the 2σ upper limit in observed flux for a point source in the inner bulge ($r < 85''$) is 5.0×10^{-16} ergs s^{-1} cm^{-2} Å^{-1} in the CsI band and 3.2×10^{-16} ergs s^{-1} cm^{-2} Å^{-1} in the CsTe band. Adopting a foreground color excess of $E(B-V) = 0.11$ (McClure and Racine 1969) and the Savage and Mathis (1979) UV reddening law, these figures convert to intrinsic monochromatic magnitudes of 16.3 and 16.7 at 1460 Å and 2380 Å, respectively. (Monochromatic magnitudes are defined as $m_\lambda = -2.5 \log F_\lambda - 21.10$, where F_λ is expressed in ergs s^{-1} cm^{-2} Å^{-1}.) Assuming $(m - M) = 24.07$ for M31 (de Vaucouleurs 1978), and using spectra in the *IUE Spectral Atlas* (Wu *et al.* 1983), the combined limiting magnitude of ~ 16.5 at 2000 Å implies that main-sequence stars hotter than ~ B0 V are not present in the bulge of M31.

Thus, our images appear to rule out young stellar populations as the source of the UV upturn in the bulge of M31. The most plausible alternatives to young populations are blue stragglers, metal-poor horizontal-branch (HB) stars, and post–asymptotic giant branch (post–AGB) stars. Though present as a minority component in many old populations, blue stragglers do not extend farther up the main sequence than about twice the turnoff mass and are much too cool to produce the observed UV upturns (Gunn, Stryker, and Tinsley 1981). Similarly, the horizontal branches of even the bluest globular clusters (van Albada, de Boer, and Dickens 1981) do not appear to contain enough very hot objects to be consistent with the UV upturn below 1500 Å. This was demonstrated quantitatively in a spectral synthesis of the *ANS* data for M31 by Wu *et al.* (1980), who found that a large contribution of O5 starlight was required in addition to a very blue HB, like that of M13, in order to fit the 1550 Å data. Using our UV imaging data for the HB of M5 (Bohlin *et al.* 1985), we confirm that if metal-poor stars contribute no more than about 5% of the V light in the M31 bulge (O'Connell 1976), the M5 HB (properly scaled) would fail to reproduce our CsI flux for the bulge by a factor of ~ 5.

On the other hand, we believe a good case can be made for post–AGB stars as the source of the far-UV flux in old populations of approximately solar metallicity. To estimate the contribution of post-AGB stars, we assume the population is in a steady state, so that the number of stars in a given evolutionary phase is proportional to the lifetime in that phase. The intrinsic V luminosity of the bulge of M31 within a circle of radius 1′ is 7×10^8 L (⊙) (de Vaucouleurs 1961), and about 50% of this radiation originates on the giant branch of the old population (e.g., O'Connell 1976; Pritchet 1977). From the models of Sweigart and Gross (1978), we compute an average V band luminosity over a red giant evolutionary track for a mass of 1.1 $M_\odot$, $Y = 0.3$, and $Z = 0.01$ of 36 L_V (⊙) and an average lifetime in the red giant phase of 1.6×10^8 yr. The number of red giants within the 1′ circle is then ~ 10^7, and the number in any subsequent phase of lifetime Δt yr is $0.06\Delta t$. During the AGB phase, these stars will lose all but a small fraction of their envelopes and evolve into hot ($T > 2 \times 10^4$ K) post–AGB stars, whose properties depend on the envelope mass available for nuclear burning during this phase (Schönberner and Weidemann 1983; Schönberner 1983).

For a core mass of 0.565 $M_\odot$ (implying 1 $M_\odot$ on the main sequence), the lifetime of the Schönberner (1983) model in the hot phase of interest for our UV observations is ~ 1×10^4 yr, with a mean flux of ~ 4.7×10^{-17} ergs s^{-1} cm^{-2} Å^{-1} per star at 1460 Å. Such stars could contribute only about 30% of the 8.45×10^{-14} ergs s^{-1} cm^{-2} Å^{-1} observed in our CsI band within 1′ of the M31 nucleus. However, Schönberner's models show that the lifetime of the post–AGB phase is extraordinarily sensitive to the core mass. A decrease in core mass of only 0.02 $M_\odot$ to 0.546 $M_\odot$ increases the lifetime by a factor of ~ 20, while decreasing the far-UV flux per star only a factor ~ 3. These slightly lower mass objects could readily produce all the observed far-UV flux from M31's bulge.

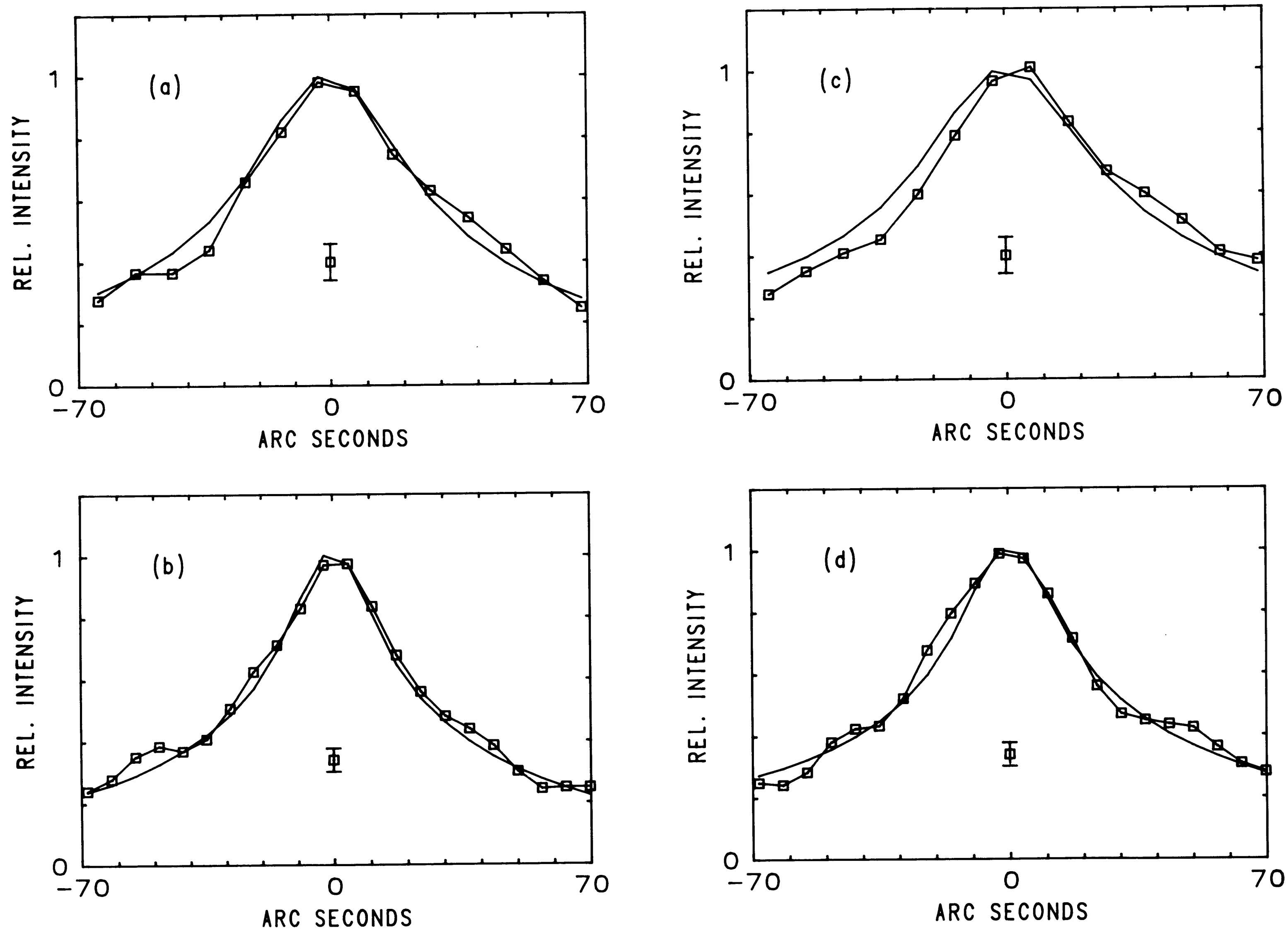

FIG. 2.—Cuts along the major and minor axis of the bulge. The major axis is taken to be at a position angle of 45° (Kent 1983). The solid lines are derived from the 6500 Å Kent data, and the lines with data points from the UV data, as described in the text. The error bars are positioned at the average intensity of the UV inside a centered circular aperture of the same area as the *ANS* satellite aperture. (*a*) Minor axis, image 10A (CsI). Northwest is positive. Relative intensity of 1 is equivalent to 1.42×10^{-17} ergs s^{-1} cm^{-2} $Å^{-1}$ $arcsec^{-2}$ in the UV. (*b*) Minor axis, image 7B (CsTe). Northwest is positive. Relative intensity of 1 is equivalent to 3.49×10^{-17} ergs s^{-1} cm^{-2} $Å^{-1}$ $arcsec^{-2}$ in the UV. (*c*) Major axis, image 10A (CsI). Southwest is positive. Relative intensity of 1 is equivalent to 1.46×10^{-17} ergs s^{-1} cm^{-2} $Å^{-1}$ $arcsec^{-2}$ in the UV. (*d*) Major axis, image 7B (CsTe). Southwest is positive. Relative intensity of 1 is equivalent to 3.54×10^{-17} ergs s^{-1} cm^{-2} $Å^{-1}$ $arcsec^{-2}$ in the UV.

Because of the uncertainty in calculations for hot post–AGB models and the crucial envelope mass loss which precedes them, we can claim no more than encouraging agreement for this interpretation of the far-UV spectra of old populations.

In the post–AGB star interpretation of the UV upturn, there is an interesting implication for the variation of UV spectra among galaxies. *IUE* data indicate that M32 has a far-UV color much redder than M31 (Johnson 1979; Bruzual 1980). This is confirmed in our imagery (see Fig. 1), from which we find that M32 has a (1460–2380 Å) color ~ 0.4 mag redder than that of M31. This difference implies a slightly larger core mass for post–AGB stars in M32, which is consistent with the increasingly strong evidence that the main-sequence turnoff in M32 is younger than in M31 (O'Connell 1980; Burstein *et al.* 1984; Rose 1985). The extreme sensitivity of post–AGB lifetime to core mass thus suggests that far-UV spectra can be used as an astrophysical probe of the stellar populations and physics of mass loss in other galactic environments (Renzini and Buzzoni 1985).

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