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A PHOTOMETRIC AND SPECTROSCOPIC SURVEY FOR YOUNG STARS IN THE HALO OF M31

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ABSTRACT

We have obtained *UBV* CCD photometry of a 0.5 deg^2 field toward the halo of M31 (the Andromeda Galaxy), using the 2.5 m Isaac Newton Telescope on La Palma. These observations have allowed us to identify nine blue stellar objects, with $(U-B) < -0.4$ and $(B-V) < 0.0$, in the magnitude range $B = 21.5$–22.5, typical of main-sequence early B-type stars at the distance of Andromeda. Hence these objects may be normal Population I stars at large distances (>3 kpc) from the plane of M31. Follow-up low-resolution spectra of these objects obtained with the William Herschel Telescope, also on La Palma, do not have the requisite signal-to-noise ratios for a definitive conclusion regarding their nature, although one source appears to be a degenerate star in the halo of our Galaxy and has thus been eliminated from the candidate list. Positive identification of Balmer absorption features in the stellar spectra at the known radial velocity shift of the Andromeda system would provide very strong evidence for the general existence of normal B-type stars in the halos of spiral galaxies.

Subject headings: galaxies: halos — galaxies: individual (M31) — stars: early-type — surveys

1. INTRODUCTION

For the last decade we have been involved in an extensive program to determine the nature and origin of faint, early-type stars at high Galactic latitudes (see the review by Keenan 1992). Our analyses of multiwavelength observations of these objects using model atmosphere calculations has led us to conclude that many of them are normal Population I OB-type stars at distances (z) from the Galactic plane ranging from approximately 2 to 25 kpc (see Conlon et al. 1990 and references therein). To date we have found $\simeq 40$ stars which we believe have been ejected from the disk, probably via cluster ejection.

We have also identified eight other stars whose short evolutionary lifetimes and large z-distances imply that they formed in the halo itself, such as SB 357 ($z = 9$ kpc; Conlon et al. 1992). Although we believe that our identifications are convincing, the possibility remains that the stars are subluminous, nearby objects whose spectra somehow mimic those of normal stars (see, for example, Tobin 1991 and references therein). This belief is strengthened by the fact that if these objects are truly distant one is led to the surprising result that star formation is currently occurring many kiloparsecs from the Galactic plane.

In view of the above, we decided to extend our work by searching for normal Population I OB-type stars in the halo of the near-edge-on spiral galaxy M31 (inclination = 15°). At the distance of M31, a main-sequence early B-type star would have a typical apparent magnitude of $B \simeq 22$ and a supergiant $B \simeq 18$. Identification of blue stars in the magnitude range $B = 18$–22 with the radial velocity of M31 ($v_r \simeq 280$ km s^{-1}), would therefore provide very strong evidence for the existence of normal OB-type stars at large distances from the planes of spiral galaxies and hence that star formation occurs in their halos. In addition, it should be possible in the longer term to determine the z-distribution of such stars, which will allow a direct comparison with theories suggested to explain their existence (Tobin 1987). In a previous study (McCausland et al. 1993), automated scans of Palomar Observatory Schmidt plate material were employed to identify blue targets. Unfortunately, this survey suffered a number of drawbacks, not the least of which was limited photometric accuracy when working near the plate limits ($B \sim 21$). With this in mind, a new survey using wide-field CCD imaging and subsequent low-resolution spectroscopy was performed.

2. OBSERVATIONS AND REDUCTIONS

2.1. *Photometry*

UBV CCD photometry toward the halo of M31 was obtained during the period 1992 September 28 to October 4, using the 2.5 m Isaac Newton Telescope at Los Roques de los Muchachos Observatory, La Palma. The prime focus camera was used together with a coated 1240 × 1152 pixel EEV CCD. The pixel size of 22.5 μm gave an image scale of 0\".56 pixel^{-1} resulting in each field covering 11'.6 × 10'.7.

The positions of the imaged fields were selected assuming a radius of 20 kpc for the galactic disk of M31 and then placing the field centers so that they were at least 3 kpc above the nearest edge of the disk. The southwest side of the halo was chosen because the corresponding part of the disk is rotating toward us. Hence, assuming that the halo corotates with the disk, the negative stellar radial velocities would be enhanced allowing them to be more easily distinguished from Galactic foreground stars.

The sky was sufficiently clear to carry out imaging on only four nights, resulting in *UBV* exposures of 15 different fields toward the halo of M31. We also obtained images of the field containing the previously studied star AND 0029+413 (McCausland et al. 1993) and of three fields in the outer edge of the disk. Including the extra halo field above, the total area of halo observed was 0.55 deg^2, corresponding to 84 kpc^2 at the distance of M31. These fields are shown relative to the M31 disk in Figure 1.

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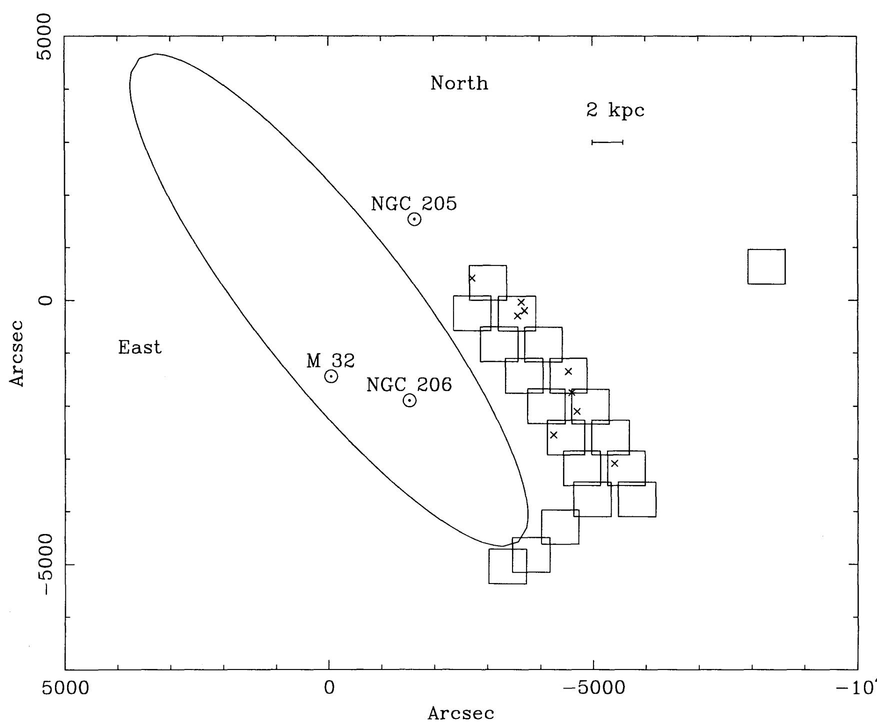

FIG. 1.—Schematic diagram showing positions of all fields imaged in *UBV* relative to the center of M31 at coordinates (0,0). The large ellipse represents the stellar disk of M31 with a radius of 20 kpc; the landmark associations M32, NGC 205, and NGC 206 are shown for reference. Crosses indicate the positions of the nine blue stellar candidates. The field at coordinates (−8200,700) contains the previously investigated star AND 0029+413 (McCausland et al. 1993).

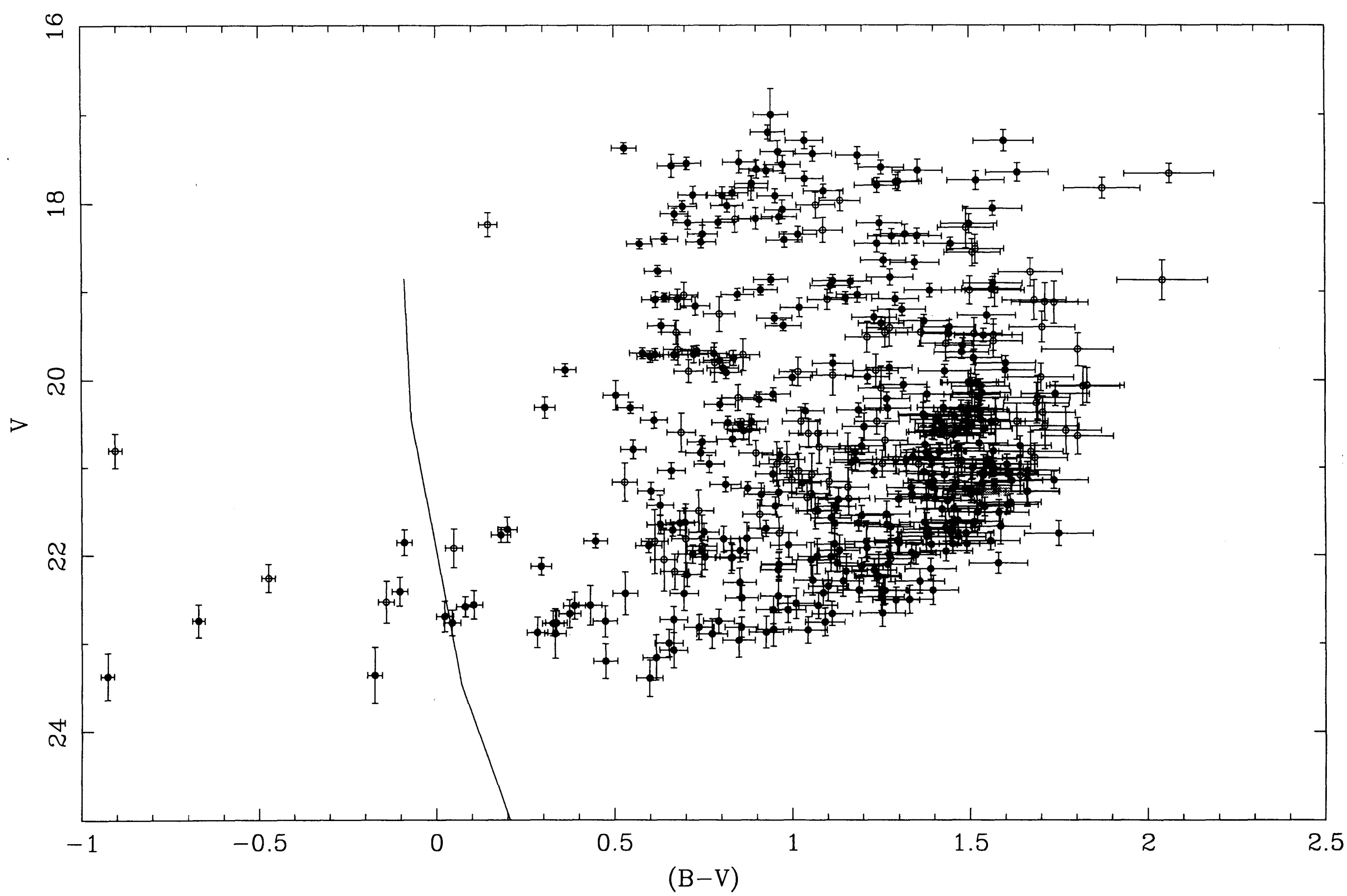

FIG. 2.—Color-magnitude diagram for a single field, showing all stellar objects found in both the *V* and *B* images. Black symbols denote objects well fitted by the point-spread function derived for the individual frames; open circles denote otherwise. The solid line shows the main sequence from O5 down to approximately B8, placed at the distance of M31 and reddened by 0.13 in $(B-V)$.

Photometry on all frames was carried out using the DAOPHOT II psf-fitting and aperture photometry routines (Stetson 1993). Apparent magnitudes were tied into the standard system using observations of standard fields from Landolt (1992) observed and reduced in the same manner as the target fields.

2.2. *Spectroscopy*

Following target selection from the CCD observations (see below), spectroscopy was carried out on the nights of 1993 September 16–20 using the ISIS spectrograph on the 4 m William Herschel Telescope, La Palma. A 158 line mm^{-1} ruled grating was employed, yielding a dispersion of 120 Å mm^{-1}. A 1024 × 1024 thinned Tektronix CCD ("TEK1") was used as detector, the 24 μm pixels corresponding to 2.88 Å $pixel^{-1}$ and wavelength coverage in the range 3900–6600 Å. Calibration exposures (flat-field and bias frames) were taken throughout the run; in addition, combined Cu-Ar/Cu-Ne arcs were taken to wavelength calibrate the spectra. Exposure times were limited to 1800 s for individual frames in order to keep contamination by radiation events down to an acceptable level. A slit width of 1".5 was used throughout the observing run.

Initial reduction of the CCD frames was carried out using FIGARO (Fuller 1989). Bias frames for all nights were checked for cosmic-ray events and global variation in counts. No global variation in bias levels above 1% was found, so the frames were debiased using the mean of the overscan region. Once debiased, the frames were trimmed to remove the overscan regions. Nightly mean flat fields were formed by co-adding tungsten lamp flats for each wavelength region and for each chip. Care was taken to ensure that all cosmic-ray events were removed from the flat fields. Large-scale gradients in illumination of the flats caused by uneven illumination of the slit and the strong wavelength dependence of the tungsten source were removed by dividing by low-order polynomial fits in both the x- and y-directions. All stellar frames were then divided by the corresponding normalized flat field from the same night, while sky subtraction was achieved by fitting low-order polynomials to sky strips either side of the stellar spectra. Extraction of the stellar spectra was achieved using the implementation within FIGARO of the optimal extraction algorithm of Horne (1986). Wavelength calibration was achieved by interpolation of arcs bracketing each stellar exposure, and the stellar spectra were then input to the package DIPSO (Howarth & Murray 1988) for further analysis.

3. RESULTS AND DISCUSSION

The (V, $B-V$) color-magnitude diagram for a typical field is shown in Figure 2; the corresponding ($U-B$, $B-V$) two-color diagram is shown in Figure 3. The galactic contribution of stars at $(B-V) > 0.5$ can clearly be seen. The solid line in the figures is a ZAMS line, shifted in the color-magnitude diagram by the distance modulus of M31 [$(m-M)_0 = 24.3$; Welch et

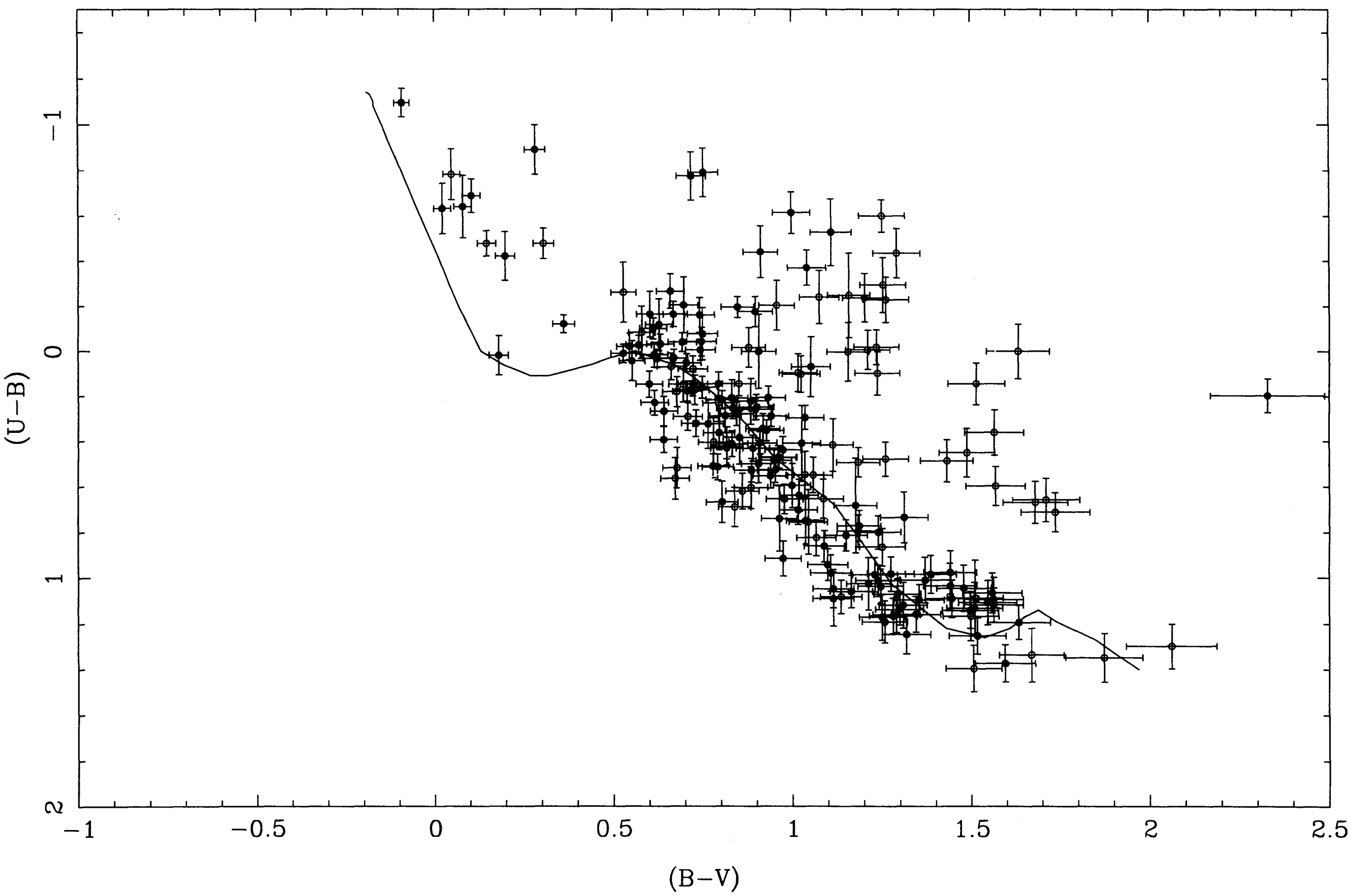

FIG. 3.—*A* ($U-B$, $B-V$) two-color diagram for the same field as Fig. 2

TABLE 1

PHOTOMETRY AND POSITIONS FOR THE NINE CANDIDATE STARS

Source Name	R.A. (1950)	Decl. (1950)	V	$(B-V)$	$(U-B)$
111-2774	$0^h34^m33^s.5$	+40°56′22″	21.5 ± 0.1	−0.07 ± 0.09	
144-511	0 33 17.2	40 30 35	21.6 ± 0.1	−0.05 ± 0.03	−0.84 ± 0.09
111-2383	0 34 45.2	40 54 47	21.7 ± 0.1	−0.08 ± 0.10	
178-17	0 32 09.4	40 08 15	21.7 ± 0.1	−0.05 ± 0.03	
144-51	0 33 22.6	40 37 13	21.8 ± 0.2	−0.03 ± 0.03	
155-184	0 33 08.9	40 24 39	21.9 ± 0.2	−0.09 ± 0.02	−1.09 ± 0.06
108-871	0 34 38.8	40 59 06	22.2 ± 0.1	−0.12 ± 0.10	−0.60 ± 0.20
34-4638	0 36 09.0	41 06 38	22.4 ± 0.1	−0.10 ± 0.11	
68-1456	0 33 48.9	40 17 15	22.4 ± 0.1	0.02 ± 0.12	

NOTE.—Coordinates were measured from the Schmidt plate scans presented in McCausland et al. 1993 and are accurate to ±2″.

al. 1986] and reddened by $E(B-V) = 0.13$. Also visible are a number of bluer objects, with one in particular at $V \simeq 21.8$, $(B-V) \simeq -0.1$, and $(U-B) \simeq -1.1$. Although the $(U-B)$ color is slightly too blue, the V magnitude and $(B-V)$ color is what would be expected for an early B-type star lying in the halo of M31.

Nine stellar-like objects were identified in the magnitude range $21.5 < V < 22.4$ with $(B-V) < 0.0$, and these are summarized in Table 1. Although they may be early-type stars in the halo of M31, there are at least two possible sources of contamination. The number of Galactic foreground objects (blue horizontal-branch stars, hot subdwarfs, and white dwarfs) is expected to be small at the faint magnitudes under consideration here. For example, from the Bahcall-Soniera Galaxy model (Bahcall 1986 and references therein), Selected Area 68 (Kron 1980) has similar Galactic coordinates to M31 and has no stars with $(B-V) > 0.0$ down to $B > 22.5$ in 0.3 deg^2 (roughly corresponding to our survey area), while Boyle (1989) has shown that there should be typically one to two white dwarfs in the area down to our magnitude limit. A poten-

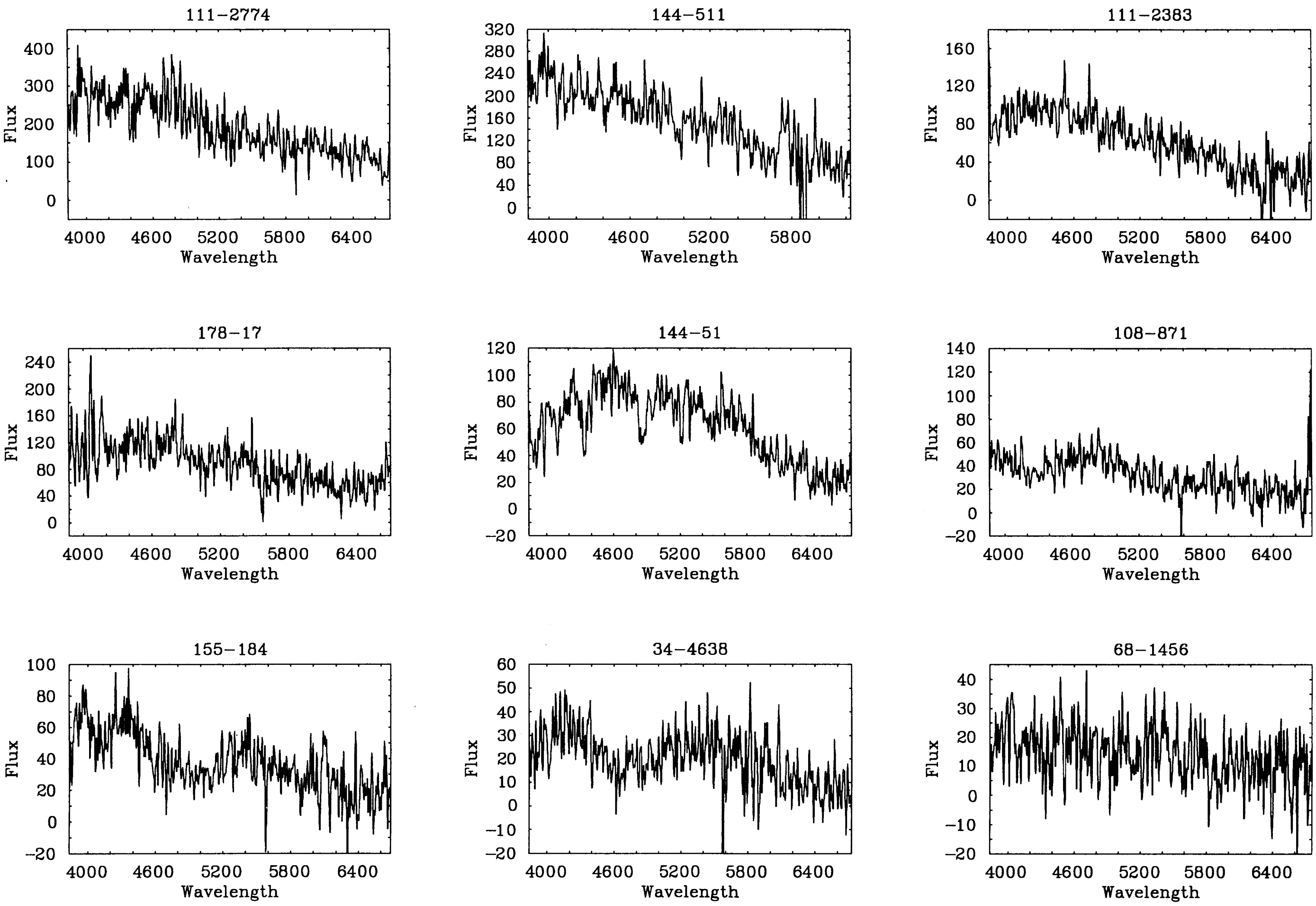

FIG. 4.—Spectra of the nine blue stellar candidates

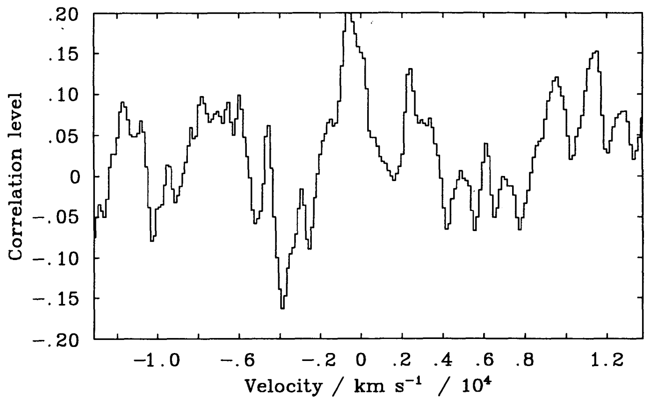

FIG. 5.—Cross-correlation (in velocity space) of a theoretical early B-type stellar spectrum with that of an M31 disk OB-type star.

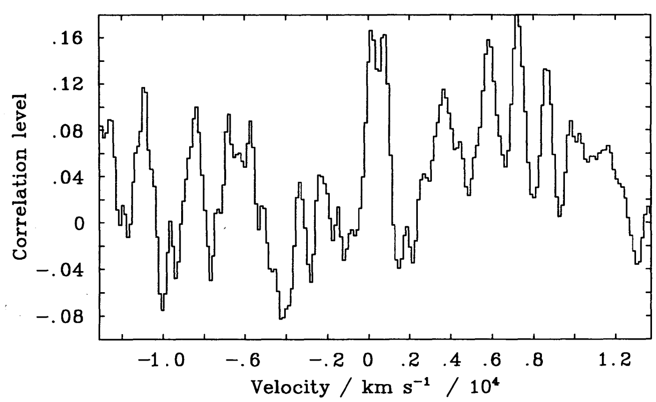

FIG. 7.—Velocity cross-correlation of a theoretical spectrum containing added noise with the same theoretical spectrum.

tially more serious contaminant are QSOs, but both theoretical and observed colors (e.g., Braccesi et al. 1980) indicate that although low-redshift objects ($z < 2$) would have a $(U-B)$ color similar to early-type stars, most should have $(B-V) > 0.0$. Spectroscopy suitable for estimating radial velocities and identifying emission features should be sufficient to eliminate both of the possibilities.

The spectra are shown in Figure 4, and although these are not flux calibrated, it is immediately apparent that the sources are blue. However, only one object (144-51) shows the Balmer series in absorption. The Hδ line has an equivalent width of 12 ± 2 Å and a radial velocity shift of -230 ± 100 km s^{-1}. The breadth and strength of the Balmer lines indicates a DA white dwarf, and the radial velocity is consistent with membership of our own Galaxy.

Cross-correlations in velocity space were performed on all the spectra using a Kurucz (1991) early B-type model stellar spectrum as a template. The model was generated at $T_{\rm eff} =$ 27,000 K and log $g = 4.3$; such atmospheric parameters yield Balmer line equivalent widths between 4.5 and 5.0 Å for Hβ, Hγ, and Hδ. Figure 5 shows the result for an M31 star with an apparent magnitude $V \sim 20.9$ from a disk OB association (Fitzsimmons et al. 1995). A clear correlation is seen at a velocity shift of -450 ± 90 km s^{-1}, indicating both membership of M31 and a superposed rotation of the galactic disk. Similar correlations for the brightest and faintest halo targets ($V \sim 21.5$ and $V \sim 22.4$, respectively) are shown in Figures 6*a* and 6*b*. No significant correlation is seen at negative radial velocities (in contrast to Fig. 5) above the noise level. As a further test, we multiplied the theoretical model into the spectrum of highest signal-to-noise ratio (i.e., the brightest star 111-2774) and performed the cross-correlation once more in an attempt to recover the theoretical spectrum. The result is shown in Figure 7, where a small signal is seen at zero radial velocity (as expected) but with higher spurious noise signals being present as well. In this procedure, the test spectra and template are perfectly matched, a situation which will not normally be the case for our observed spectra. We note that our failure to obtain sufficient S/N to detect possible hydrogen line absorption features is due to the effects of sky brightness on our observations (even during dark time) rather than a lack of integration time. Observations with a telescope of larger aperture than the WHT will be required to significantly reduce these effects.

4. CONCLUSION

An excess of early-type stellar objects has been detected in the direction of the halo of M31 which possess the magnitude and color ranges expected of B-type stars at that distance. Low-resolution spectroscopy, obtained on a 4 m aperture telescope, has indicated that one of the nine objects identified is a

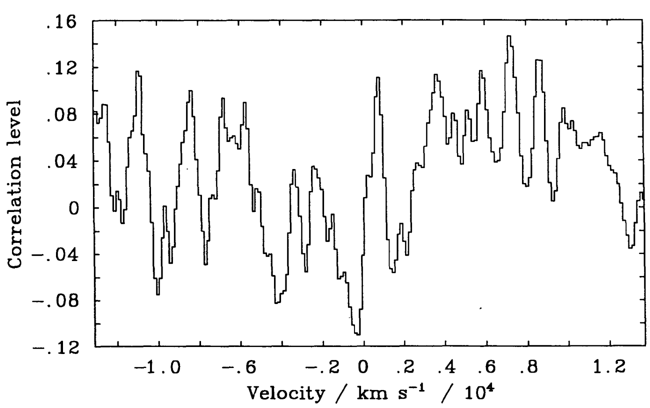

FIG. 6*a*

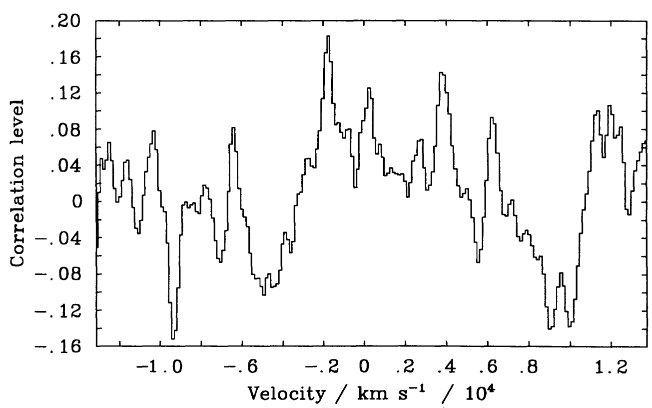

FIG. 6*b*

FIG. 6.—Velocity cross-correlations of (*a*) the brightest and (*b*) the faintest halo candidates

white dwarf. The remaining eight objects do not have spectra of high enough signal-to-noise ratio to determine their nature. As noted above, a larger telescope, such as the current Keck facility or upcoming Gemini, is required to detect possible hydrogen line absorption features and hence investigate the possibility that these objects are young main-sequence B-type stars in the halo of M31. Alternatively, it may be possible to obtain UV spectra on the refurbished *Hubble Space Telescope*. We hope to undertake such observations in the near future.

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