# DISCOVERY OF CANDIDATE LUMINOUS BLUE VARIABLES IN M31<sup>1</sup>

# N. L. KING AND R. A. M. WALTERBOS<sup>2</sup>

Astronomy Department, New Mexico State University, Box 30001, Department 4500, Las Cruces, NM 88003; nking@nmsu.edu, rwalterb@nmsu.edu

AND

R. Braun

Netherlands Foundation for Research in Astronomy, NFRA, P.O. Box 2, NL-7990 AA Dwingeloo, Netherlands; rbraun@nfra.nl Received 1997 September 29; accepted 1998 June 10

## ABSTRACT

Luminous blue variables (LBVs) constitute a short-lived, eruptive phase in the evolution of some of the most massive stars. Only a handful have yet been identified in the Galaxy and in each of the nearby galaxies; there are four known LBVs in M31. We have found an efficient method to identify candidate LBV stars in nearby galaxies. The candidates are identified in a pair of deep, continuum-subtracted narrowband H $\alpha$  and [S II] images as objects with extremely low [S II] to H $\alpha$  ratios, and with coincident stellar objects in continuum images. Five of the most promising new candidates identified by these criteria in the northeastern half of M31 were subsequently confirmed by optical spectroscopy to show spectra similar to the previously identified M31 LBV, HS var 15. These five candidates also have much in common with B[e] stars, of which none were known to exist in M31. They are bright H $\alpha$  sources, (120  $L_{\odot} < L_{H\alpha} < 1300 L_{\odot}$ ) with no detectable [S II] emission, large H $\alpha$  equivalent widths (-60 to -400 Å), and broad wings on the H $\alpha$  profiles (FWZI = 1200-2000 km s<sup>-1</sup>). Most candidates have Fe II emission. We discuss the environments of the candidates and find that many objects are likely older than several million years because they tend not to be located inside bright H II regions. We predict, based on the current results, that at least 20-25 LBV/B[e] candidates may be present in M31.

Subject headings: galaxies: individual (M31) — Local Group — stars: early-type —

stars: emission-line, Be — stars: mass loss —

stars: variables: other (luminous blue variables)

## 1. INTRODUCTION

The post-main-sequence evolution of massive stars, in particular the transition of a blue supergiant to a Wolf-Rayet (W-R) star, is still poorly understood. In this transition regime, mass loss is a fundamental driver of stellar evolution. Among the transitory objects are luminous blue variables (LBVs). These objects, whose most famous member is  $\eta$  Car, have dense winds and irregular, sometimes eruptive mass loss (Humphreys & Davidson 1994). Detailed knowledge of the properties of stars in this part of the H-R diagram is crucial for improving theories for the evolution of massive stars (see, e.g., Langer et al. 1994).

LBVs inhabit the upper-left portion of the H-R diagram along with the other emission-line stars of types Ofpe/WN9 and B[e] supergiants. The different types are thought to be related (Bohannan & Walborn 1989), but with so few members known within each category the evolutionary sequence is not clear. Two Ofpe/WN9 stars have been seen erupting into LBV status (R127, Stahl & Wolf 1986; HDE 269582, Bohannan 1989), a classified B[e] star now designated an LBV (S22, Shore 1992), and another known LBV when in its hot state resembles an Ofpe/WN9 star (AG Car, Stahl 1986). In M31, only four LBVs have been identified, the first two by Hubble (1929, not recognized as an LBV at that time), and the last one 25 yr ago (Rosino & Bianchini 1973: see Humphreys & Davidson 1994 for a recent review). One Ofpe/WN9 star has been discovered (Massey 1997), and there are no reports of B[e] stars.

<sup>1</sup> Data obtained at ARC 3.5 m and KPNO 4 m telescopes.

The methods for identifying these objects have been different for each type. LBVs are classified as such when seen in outburst-a photometrically defined membership. The formal designation requires a star of the upper H-R diagram to have an eruption that displays a visual change of  $\geq 2 \mod$  (Humphreys & Davidson 1994). In practice, finding them may require long-term (several decades) monitoring of galaxies. B[e] and Ofpe/WN9 stars have been identified spectroscopically. The candidates can be found as hot stars with far-UV and UBV photometry (Humphreys, Massey, & Freedman 1990; Massey et al. 1995), and as compact stellar sources in an Ha prism or imaging surveys. The search methods result in large lists of sources that may be LBVs, B[e], or Ofpe/WN9 stars but could also be compact H II regions, supernova remnants (SNRs), and planetary nebulas (PNs). Spectroscopic identification of all candidates then requires substantial amounts of telescope time. We have found a good way to detect bright stars with high mass-loss rates from emission-line images in H $\alpha$  and [S II]. The addition of [S II] images helps to eliminate H II regions and SNRs from our target list. Our method offers a way to survey nearby galaxies systematically, which potentially increases the numbers of identified LBVs and B[e] supergiants by factors of 3-5. We will demonstrate the search method for star-forming regions in M31.

In § 2 we discuss the observations and search method. In § 3 we analyze the spectra and discuss the properties of the candidates. In § 4 we discuss their environments, and we briefly summarize our results in § 5.

#### 2. OBSERVATIONS

The data sets relevant to this study include a deep imaging survey of M31 in H $\alpha$  and [S II] (Walterbos &

<sup>&</sup>lt;sup>2</sup> Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

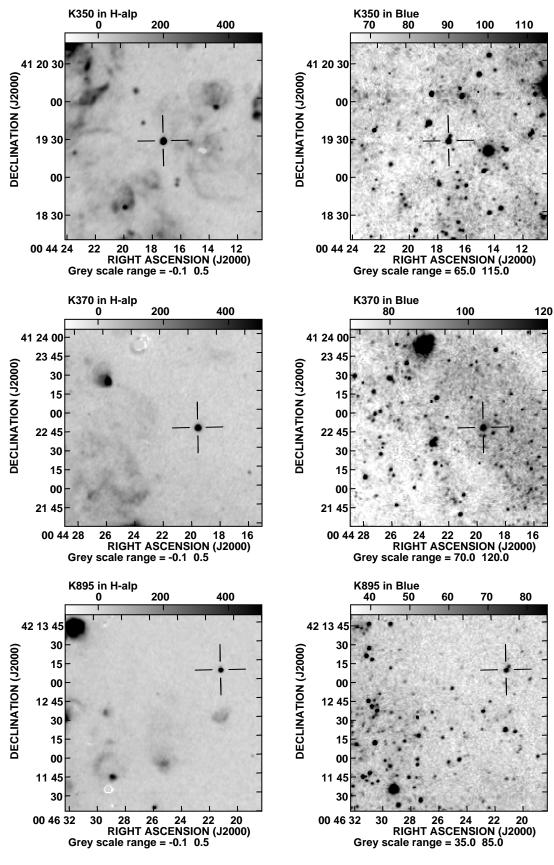
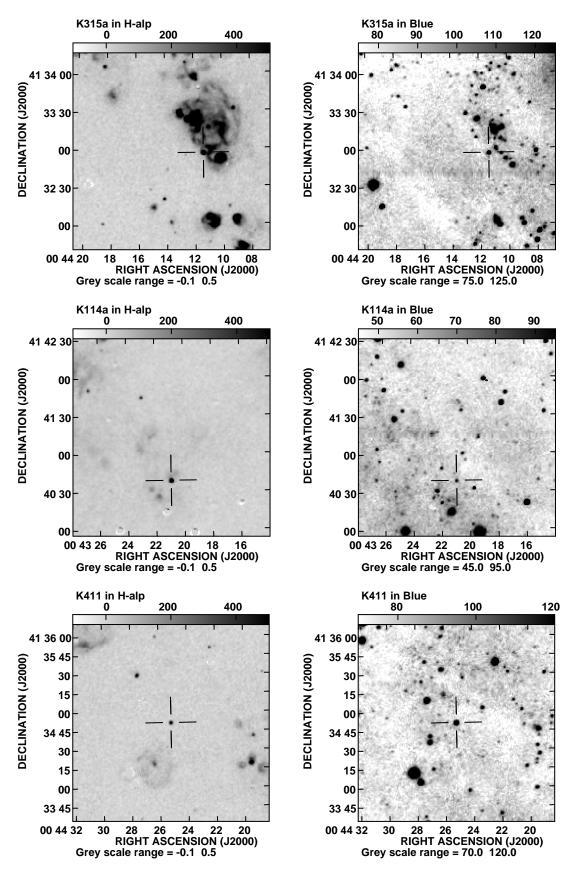




FIG. 1*a*.—H $\alpha$  and *B* images of the six objects. Identifications for all emission-line nebulae are given in WB92. Object K370 is the previously identified LBV V15. The *B* images serve as finding charts but also illustrate dust lanes and surrounding OB associations: (*a*) K350, K370, and K895; (*b*) K315a, K114a, and K411.





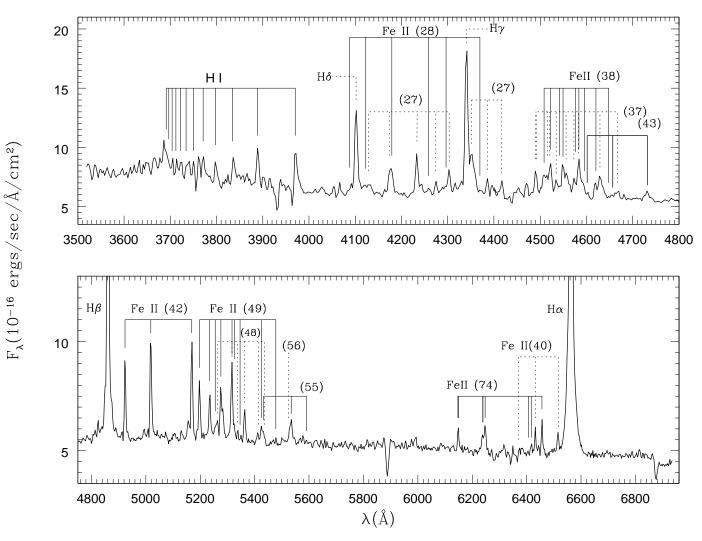


FIG. 2.—Spectrum of K370 obtained with the KPNO 4 m telescope in 1991 November. The major lines are identified.

Braun 1992, hereafter WB92), and long-slit spectroscopy with the KPNO 4 m (Greenawalt, Walterbos, & Braun 1997) and ARC 3.5 m telescopes. The KPNO 36 inch telescope was used to image 19 fields in M31 through 27 Å filters centered on the H $\alpha$  and [S II] emission lines and broadband *B*. Each field measured 6.7 × 6.7 arcmin<sup>2</sup>. The combined survey covered only the major spiral-arm sections in the northeastern half of M31 and not the entire galaxy (see Fig. 1 of WB92). The typical resolution of the images is 2'', which corresponds to 6.7 pc at an assumed distance of 690 kpc. Exposures of 40 minutes each in H $\alpha$  and [S II] resulted in lower limits for detection of L =

Object	$L_{ m Hlpha}^{\ \ b} (L_{\odot})$	W <sub>H</sub> α (Å)	$V_{\text{term}}$ (km s <sup>-1</sup> )	Catalog Number <sup>c</sup>	$\dot{M}$ $(M_{\odot} \text{ yr}^{-1})$
K350	1312.0	$-206 \pm 13$		268914	
K315a	360	$-115 \pm 12$		339869	
K895	374	$-223 \pm 29$		459351	
K114a	287	$-392 \pm 42$		383221	
K411	118	$-62 \pm 5$	320	351220	1.4E - 5
$V15 = K370 \dots$	1109	$-197 \pm 7$	310	282734	0.7E - 5
AE And			100 <sup>d</sup>		
AF And	1145°	$-65^{e}$	150 <sup>d</sup> , 350 <sup>f</sup>		1.9E - 5
Var A-1	1175°	-65°	200 <sup>f</sup>		

 TABLE 1

 Properties of the Candidates and Luminous Blue Variables<sup>a</sup>

<sup>a</sup> Coordinates for the K sources are in WB92, except K315a (RA[2000] 0:44:11.4, Decl.[2000] 41:32:56.9) and K114a (RA[2000] 0:43:20.9, DEC[2000] 41:40:39.2)

<sup>b</sup> For a distance of 690 Mpc, without reddening correction.

° Magnier et al. 1992.

<sup>d</sup> Szeifert et al. 1996.

<sup>e</sup> Gallagher et al. 1981.

<sup>f</sup> Kenyon & Gallagher 1985.

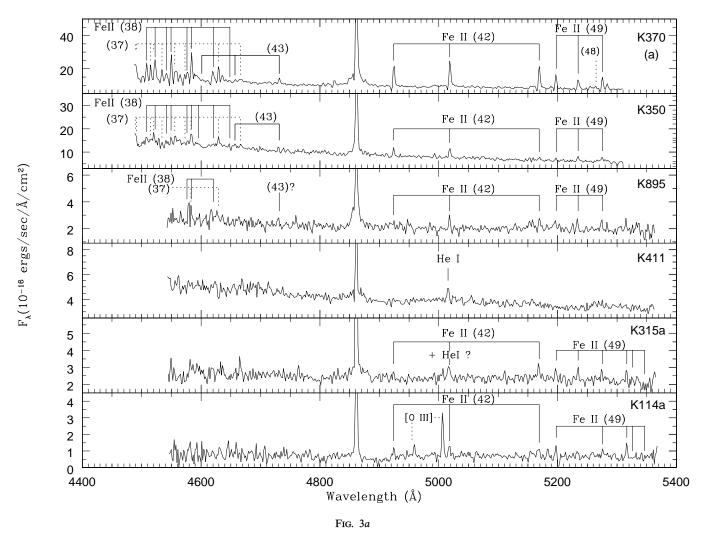


FIG. 3.—Spectra of all objects taken with the ARC 3.5 m telescope in 1995 September. *Top to bottom:* K370, K350, K895, K411, K315a, and K114a. Note the similarity in the spectra between K370 and the newly discovered sources. Spectra have been velocity-shifted to the rest frames of the H Balmer cores: (a) blue spectra, (b) red spectra.

 $5.7\times10^{34}~{\rm ergs~s^{-1}}$  (15  $L_{\odot}$ ). Targets relevant for this paper are identified in Figure 1.

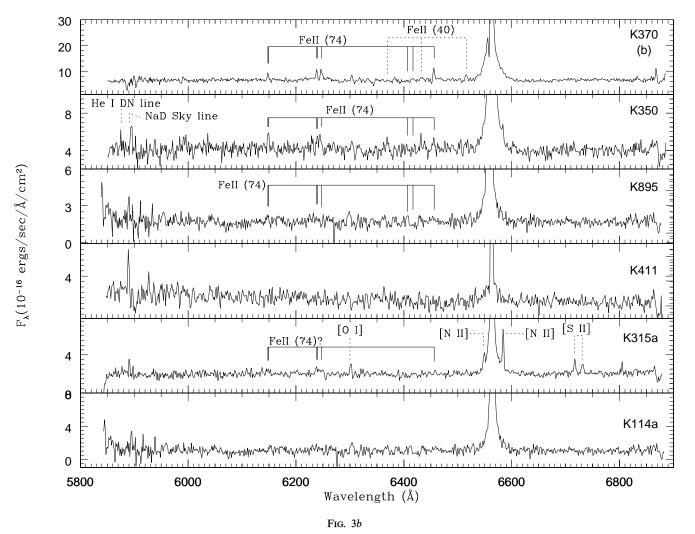
The KPNO spectra of the LBV HS var 15 (hereafter V15; K370 of WB92 survey) were obtained in 1991 November with the RC spectrograph on the 4 m telescope. We used a  $\sim 2'' \times 6'$  slit that was oriented close to or at the parallactic angle. Two spectra were obtained for V15 with slightly different central wavelengths to span the range 3500–7000 Å. The exposure time per spectrum was 1800 s. Grating KPC-10A produced a dispersion of 2.78 Å pixel<sup>-1</sup>. The spectral resolution is about 8.5 Å. The combined spectrum is shown in Figure 2.

ARC 3.5 m spectra of seven targets and V15 were obtained with the Double Imaging Spectrograph (DIS) in high-resolution mode with a 2" slit in 1995 September. A dichroic splits the beam into blue and red portions that are dispersed onto a 512 × 512 Tek chip with 27  $\mu$ m pixels, and an 800 × 800 TI chip with 15  $\mu$ m pixels, which produces scales of 1".086 and 0".610 pixel<sup>-1</sup>, respectively, for the blue and the red. The resulting wavelength coverage was 4480–5300 Å, with a spectral resolution of ~3.7 Å, and 5840–6880 Å, with a spectral resolution of ~3.1 Å. All spectra were obtained at airmasses for which the differential refraction over this small wavelength range did not cause any

problems for slit orientations different from the parallactic angle; however, small tracking problems may have resulted in some of our objects not being centered in the slit at all times. Two exposures of equal length were taken, which resulted in total integration times of 2400 s. Cosmic rays were identified by comparing the two exposures and were removed by editing the individual frames. Spectra of a quartz lamp served to flatten the individual frames. For flux calibration, the spectrophotometric standard PG 0216+032 (Massey et al. 1988) was observed. The wavelength calibration was determined from He, Ne, and Ar arc lamp exposures.

## 2.1. Search Method

The H $\alpha$  and [S II] imaging data set had previously been used to study H II regions (WB92), supernova remnants (Braun & Walterbos 1993), and diffuse ionized gas (Walterbos & Braun 1994) in M31. We found that undiscovered treasures still remain. In the process of cataloging emission-line sources, a set of interesting objects emerged. These were compact *B*-band and H $\alpha$  sources that were bright in H $\alpha$  (~70  $L_{\odot} < L_{H\alpha} < ~1300 L_{\odot}$ ) but had no detectable [S II] emission to quite low upper limits, sometimes as low as 1% of the H $\alpha$  flux. The low line ratio dis-



tinguishes these sources from normal H II regions and SNRs. Normal H II regions have S II/H $\alpha$  of 0.15–0.35 (see, e.g., WB92), while SNRs typically have S II/H $\alpha$  > 0.4. The brighter compact H $\alpha$  sources that we find can also be distinguished from PNs on the basis of their higher H $\alpha$  luminosity, since PNs are only found at  $L_{H\alpha} \leq 70 L_{\odot}$ (Vassiliadis, Dopita, & Morgan 1992). In addition, the central stars of PNs have continuum luminosities less than about  $M_V = -4$  (see, e.g., Schönberner 1981), which corresponds to about  $m_V = 20.2$  within M31 in the absence of additional extinction. This is near the limiting magnitude of our continuum-imaging data ( $m_B \sim 21$ ) and about 3–4 mag fainter than the confirmed LBVs in M31.

A justification for the lack of [S II] as a search criteria is evident from spectra of known LBVs. In Gallagher, Kenyon, & Hege (1981) spectra of the M31 LBVs AF And and Var A-1 And, [S II] is not detected. We do not see [S II]in the M31 LBV V15 (this paper). A spectrogram of the LMC LBV SDOR shows only very weak [S II], which is less than 4% above the continuum (Leitherer et al. 1985). We also examined the possible visibility of circumstellar nebular [S II] in unresolved sources by looking at resolved Galactic LBVs. AG Car and HR Car have circumstellar nebulae that show [S II] emission. From Nota et al. (1997) we estimate that the nebular [S II] flux is 300 times weaker than the stellar wind H $\alpha$  flux. A similar exercise using the nebular and stellar fluxes of AG Car (Smith et al. 1997; Nota et al. 1992; Viotti, Polcaro, & Rossi 1993) shows that the nebular [S II] is less than 5% of the stellar wind H $\alpha$ . This implies that a survey such as ours of a nearby galaxy would not have detected [S II] in stars with extended nebulae because the nebular emission would be weak and diluted in the larger pixel scale.

In the fall of 1991 we obtained spectra for one of the objects, K370, using the KPNO 4 m telescope. The object showed spectacular broad wings on the Balmer lines and a spectrum rich in emission lines not normally observed in H II regions. Only after taking the data did we learn that the object was a known LBV, Hubble-Sandage Variable 15 (V15; Hubble 1929). The spectrum is shown in Figure 2.

On the premise that similar objects might also be LBVs, we obtained spectra of seven compact targets with a high H $\alpha$  luminosity, and K370 again, using DIS on the ARC 3.5 m telescope in the fall of 1995. Of the seven new targets, two displayed normal H II region spectra. These were the objects K595 and K955. Both proved to have substantial and peaked [S II] emission upon reinspection of the narrowband images (19% and 13% of H $\alpha$ , respectively) and hence should not have been included in the target list. The remaining five targets had similar optical spectra (see Fig. 3), strong hydrogen Balmer lines with broad wings (see Fig. 4), presumably due to electron scattering (Bernat & Lambert 1978), and narrow Fe II emission lines (except for K411). Thus, all of the compact bright H $\alpha$  targets that have a

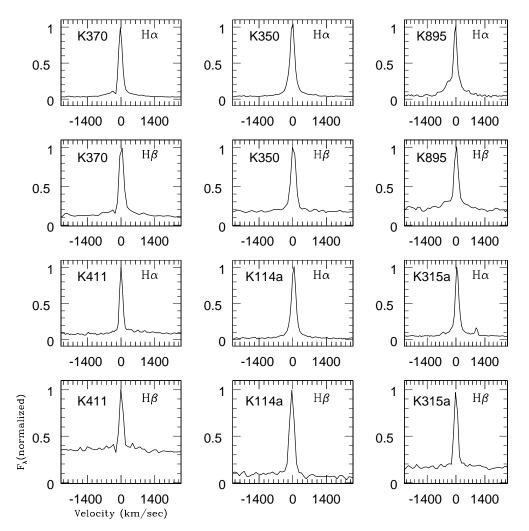


FIG. 4.—Hydrogen Balmer profiles of the candidates. The broad wings on the Balmer lines may be due to electron scattering (Bernat & Lambert 1978). Note the P Cygni profiles in K370 H $\alpha$ , K370 H $\beta$ , and K411 H $\beta$ , and the asymmetric profiles in H $\alpha$  and H $\beta$  of K895 and K350.

coincident continuum source and lack [S II] turn out to resemble one particular class of objects (see Fig. 5 for their positions in a color-magnitude diagram).

We also note that one other known LBV in M31, Var A-1 And, was imaged in the WB92 data set and made our target list. We have not yet observed it with the ARC 3.5 m telescope, but spectra can be found in Gallagher et al. (1981) and Kenyon & Gallagher (1985). The spectra of Var A-1 also resemble the spectra of the candidates in this paper.

In Table 1 relevant information on the candidate (cLBVs) and the known LBVs of M31 are listed. Finding charts for the LBVs and V15 are presented in Figure 1.

# 3. RESULTS

#### 3.1. Analysis of the Spectra

The spectra were Doppler shifted to the central rest frames of the H Balmer cores to make line identifications using Tarafdar & Apparao (1994) and Moore (1945). Radial velocities for each object were determined from Gaussian fits to multiple lines in the blue and red spectra. The radial velocity errors are the standard deviations of the Gaussian fits to the emission lines of each object. Radial velocities were transformed to heliocentric velocities using the task "rvcorrect" of IRAF, which corrects the observations for motion of the Earth, Moon, and Sun.

The KPNO spectra of K370 (V15) span a larger wavelength range than the ARC 3.5 m spectra, but at a lower resolution. Line identifications were made using both ARC and KPNO spectra. The Balmer lines display P Cygni profiles (see Fig. 3a). The next strongest emission lines are the Fe II mulitiplets of 27, 37, 38, 40, 42, 48, 49, and 74, and they also display P-Cygni profiles (see Fig. 3). We also find weak emission from Fe II 28, 43, 55, 56,  $c^4D-z^4D^0$ , and  $a^6S-a^6D$ . There is no evidence of [Fe II] or He II. Some lines of He I may be present, but in all cases the wavelengths coincide with identified members of permitted Fe II multiplets, where the Fe II emission is a more likely identification because nearly all of the multiplet members are present, and the radial velocity of the Fe II identification agrees better with that derived from the Balmer lines. K370 has a blue continuum. The radial velocity derived from the Doppler-shifted cores of the hydrogen Balmer lines is  $-218 \pm 20$  km s<sup>-1</sup>. The heliocentric velocity is  $-210 \pm 20 \text{ km s}^{-1}$ .

The spectra of K350 show the presence of Fe II emission from the multiplets of 37, 38, 43, 42, 40, and 74. There is probably also weak emission from the multiplet 49. Examination of the two-dimensional slit spectra shows that the lines near He I  $\lambda$ 5876 and Na D  $\lambda$ 5891 are residuals from the subtraction of the strong night-sky lines. K350 has a blue

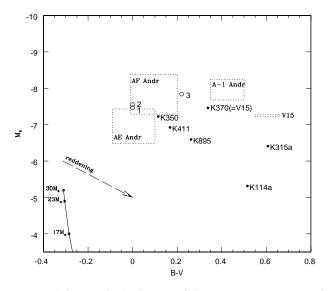


FIG. 5.—Color-magnitude diagram of the M31 LBVs + cLBVs. The boxes outlined in dashes are photometry from Szeifert et al. (1996) and Humphreys et al. (1984) of the known LBVs, spanning quiescent and outburst phases. The filled dots are photometry from Magnier et al. (1992) of the cLBVs + LBV V15 that has not been dereddened. A distance modulus of 24.43 (Freedman & Madore 1990) has been applied. A standard reddening vector with R = 3.2 has been drawn. Open circles 1, 2, and 3 are the estimated dereddened positions of K411, AF And, and V15, respectively. The MS curve (*solid line*) in the lower left-hand corner is taken from Popper (1980) and Lang (1992).

continuum. Its heliocentric radial velocity is  $-247 \pm 20$  km s<sup>-1</sup>.

Object K895 shows weak emission from Fe II multiplets of 37, 38, 42, 49, and 74. There may also be weak emission from multiplets 40, 43, and 48. K895 has a blue continuum. The derived heliocentric radial velocity is  $2 \pm 15 \text{ km s}^{-1}$ .

The spectrum of K411 has He I  $\lambda$ 5016. We do not detect Fe II. H $\beta$  displays a P-Cygni profile, and the object has a blue continuum. The heliocentric radial velocity is  $-7 \pm 8$  km s<sup>-1</sup>.

K315a shows weak emission from Fe II (42) and (49), and possibly He I  $\lambda$ 5016 blended with Fe II (42)  $\lambda$ 5018. Emission from multiplet 74 may also be present. The lines of [N II]  $\lambda\lambda$ 6548 and 6583, and [S II]  $\lambda\lambda$ 6716 and 6731 are clearly seen, but the [S II] emission and much of the [N II] emission appears to come from the H II region in which K315a is found. These nebular lines are left in the spectra because the spectral image is not sampled well enough in the spatial dimension for proper subtraction. The [O I]  $\lambda$ 6300 line is detected at 3.5  $\sigma$  but appears to be a residual of night-sky subtraction. The heliocentric radial velocity is  $-95 \pm 39$  km s<sup>-1</sup>.

K114a shows emission from the Fe II multiplets of 42 and 49 and from  $[O III] \lambda\lambda 4959$  and 5007. Close inspection of the spectral image shows that the  $[O III] \lambda 4959$  emission originates in an area surrounding K114a that is 1.4 times the linear size of the H $\beta$ -emitting region. The [O III] section is not large enough to make a proper background subtraction. Other nebular lines such as those of [N II] and [S II] in the red spectra are extended across the entire image and therefore were easy to subtract. The heliocentric velocity is  $-232 + 41 \text{ km s}^{-1}$ .

All five objects display spectra similar to the known LBV, K370 (V15), in that they are bright stars that show strong H $\alpha$  emission and sometimes Fe II emission. These character-

istics are also shared by B[e] stars (see, e.g., Zickgraf et al. 1986; Zickgraf 1989). We do not, however, find clear evidence for [Fe II] or other common forbidden lines in B[e] stars that make the possible B[e] classification for these objects tentative. We are in the process of obtaining IR photometry of all candidates that may help to further constrain their types (King, Gallagher, & Walterbos 1998). Infrared excess due to disk emission should begin to be evident in the K band if the stars are B[e] stars.

Only one object, K411, clearly shows evidence of He I emission. For the other objects, He I in the blue part of the spectrum could be confused with Fe II or strong sky lines, but the red 6678 Å line would lie in a featureless part of the spectrum. If the He were fully ionized throughout the H<sup>+</sup> nebulae, we would have expected  $f_{6678}/f_{6563}$  to be 0.013. The 3  $\sigma$  upper limits are at least a factor 2 below 0.013 in all cases. The lack of He I for most of the objects, along with the evidence for a dense slow wind suggests that all objects may be in an apparently cool phase, where the visual luminosity is at its highest. The colors of the objects suggest this as well (see Fig. 5); however, the broadband magnitudes are not very accurate. They are also from different epochs than the spectra.

The sources investigated so far are the brightest  $H\alpha$  sources of our target list, and we are not surprised to find that none of them resembles the Ofpe/WN9 type. Nota et al. (1996) found that the Balmer emission-line equivalent widths are much larger for B[e] stars than for Ofpe/WN9 stars. Spectroscopy of our dimmer  $H\alpha$  targets may reveal Ofpe/WN9 stars.

## 3.2. Mass-Loss Estimates from $H\alpha$

We estimated rough mass-loss rates for K411, V15, and the LBV AF And. We have included AF And in this study to compare the value we get here with the value obtained through non-LTE modeling of the H $\alpha$  profile (Szeifert et al. 1996). To get the mass-loss rates we used the generalized curve of growth for H $\alpha$  from Puls et al. (1996; eq. [52]). The relation was constructed for O stars but is also appropriate for the cooler and optically thick winds of B-supergiants. The emission is taken to arise from a stationary, smooth, and spherically symmetric wind. This may not be the best assumption for LBVs and B[e] stars since some have asymmetric winds (Ignace, Cassinelli, & Bjorkman 1996), but the resulting mass-loss rate should be a reasonable rough estimate. The formula requires for each object the  $H\alpha$  equivalent width, terminal velocity of the wind, radius of the star, and effective temperature of the star. Results are listed in Table 1.

For AF And, the stellar radius and temperature were taken from Szeifert et al. (1996) to be 63  $R_{\odot}$  and 30,000 K, respectively. The terminal velocity, 350 km s<sup>-1</sup>, and H $\alpha$  equivalent width, 65 Å, were found in Kenyon & Gallagher (1985) and Gallagher et al. (1981). Using the Puls et al. (1996) curve-of-growth equation we determined a mass-loss rate of  $1.9 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ , which is similar to the  $3 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$  found by Szeifert et al. (1996).

For K411 and K370 we had to estimate stellar parameters by assuming that their dereddened positions in an  $M_V$ versus B - V diagram, when coincident with the dereddened position of known LBVs, implied similar temperatures and luminosities (see Fig. 5). Note that these rough estimates neglect the possibility that any of the objects are in different transitional phases, e.g., outburst versus quiescence. We use the dereddened  $M_V$  versus B-V positions to roughly correct for the bolometric information that we lack. The reddenings of all objects (see Fig. 5) were estimated using half the value of  $A_V$  determined from the radial distributions of H I column densities in M31 (see Fig. 11 of Walterbos & Schwering 1987), plus a foreground Galactic extinction toward M31 of  $E(B-V) \sim 0.08$  (Massey, Armandroff, & Conti 1986) and a standard Galactic extinction curve with R = 3.2 (Cardelli, Clayton, & Mathis 1989).

A temperature of 30,000 K was adopted for K411 because it had a B-V similar to that of AF And. The temperature seems reasonable considering the presence of He I in the spectra. K411 is 0.5 mag dimmer visually, so the adopted radius 60  $R_{\odot}$  was determined by scaling the ratio of radii by the square root of the ratio of the luminosities. The  $H\alpha$ luminosity and H $\alpha$  equivalent width were determined from our spectra to be 118  $L_{\odot}$  and 62 Å, respectively, while the terminal velocity was found to be 320 km s<sup>-1</sup> from the blueward edge of the absorption dip in the P Cygni profile. The temperature for V15 was assumed to be similar to that of Var B in M33 (9000 K; Szeifert et al. 1996) because of their common dereddened B-V loci. We estimated a radius of 140  $R_{\odot}$  by assuming that V15 is about 2.5 mag dimmer than Var B, whose radius and luminosity are found in Szeifert et al. (1996). From our spectra, we found a terminal velocity of 310 km s<sup>-1</sup> and an H $\alpha$  equivalent width of 197 Å. The Puls et al. (1996) formula yielded a mass-loss rate of  $0.6 \times 10^{-5} M_{\odot}$  yr<sup>-1</sup> for V15 and  $1.6 \times 10^{-5} M_{\odot}$  yr<sup>-1</sup> for K411. These mass-loss rates seem reasonable for objects in eruption (Humphreys & Davidson 1994; Leitherer 1997). The largest uncertainties are in the extinction corrections.

## 3.3. Properties of the Nebulae and Stars

We carefully checked whether any of the nebulae were spatially resolved. If this were the case, we would be dealing with large (several parsec-size) nebulae with considerable mass ( $\geq$  few  $M_{\odot}$ ). This would make a strong case for either long-term high mass-loss rates, or periodic super-high mass-loss rates as observed in LBVs (see, e.g., Nota & Clampin 1997). We have obtained subarcsecond H $\alpha$  images of these objects using the WIYN 3.5 m telescope (King et al. 1998), from which we see that their diameters are less than 2 or 3 pc. We also note that the absence of [S II] and other forbidden lines, if caused by collisional de-excitation, strongly favors dense, hence small, nebulae, and therefore our results are not surprising.

The spectra of K315a and K114a show evidence of circumstellar nebulae. K315a displays emission from [N II] and [S II], while the slit spectra of K114a show that it is surrounded by an extended area of [O III] emission.

Figure 5 shows the positions of the candidates and known LBVs of M31 in a color-magnitude diagram (cLBV photometry is from Magnier et al. 1992, and LBV photometry is from Szeifert et al. 1996 and Humphreys et al. 1984). In the previous section we estimated that K411 is near the position of AF And in an H-R diagram, and V15 is at least 2.5 mag below Var B. This places K411 with the brighter group of LBVs such as Var 83, AG Car, and R127 (Fig. 20 of Szeifert et al. 1996) and places V15 among the lower luminosity sources such as HR Car, R40, and R71 (Szeifert et al. 1996). K895 and K350 have dereddened visual magnitudes and colors that are similar to K411, which implies that they can also be placed with the higher luminosity sources. K315a and K114a are dim and red, but their spectral-energy distributions (King et al. 1998) hint that these may be highly reddened sources.

#### 4. DISCUSSION

## 4.1. Total Number of Luminous Blue Variable/B[e] Candidates in M31

It is clear that we have identified a successful method for detecting luminous stars with dense, slow winds. The new candidates in M31 are not the only recently suggested LBVs in local group galaxies (M33, Massey et al. 1996; M33, Corral 1996). The detection technique of Massey et al. (1996) is complementary in that it is most sensitive to hot stars, while we appear to pick up mostly cooler objects. We may find hotter stars in our list of lower H $\alpha$  luminosity objects. The technique of Corral (1996) has also been successful, but the success rate was less (five candidates emerged from 30 target spectra). Nevertheless, we will eventually be forced to consider compact sources with [S II] emission if we wish to detect extended, and hence less dense, LBV nebulae. The combination of UIT and H $\alpha$  images could be particularly useful in selecting those objects, as demonstrated by Massey et al. (1996).

From our results, we can easily estimate the minimum number of these candidate LBV/B[e] stars that should be present in M31. Using a star formation rate of 0.35  $M_{\odot}$  $yr^{-1}$  for M31 (Walterbos & Kennicutt 1988), a lifetime of the LBV phase as  $2 \times 10^4$  yr (Humphreys & Davidson 1994), initial mass function (IMF) slope between -2.3 and -2.0 (Massey et al. 1995), a lower mass limit of 40  $M_{\odot}$  to become an LBV, and the assumption of a steady state star formation rate, we would expect that five to 15 LBVs should be present in M31 (see Walterbos 1997). A larger number of LBVs would possibly mean that the lifetime of the LBV phase is longer, the upper mass limit lower, or the IMF slope flatter than -2.0. The latter is unlikely, so improving upon the samples of LBVs can help in constraining lifetimes and mass limits. We have obtained spectra for five of our candidates, and at least five more good targets remain on the list. Should they also turn out to be candidate LBVs, we will have found 10 of these objects in 40% of the star-forming regions of M31. Assuming a similar success rate for the remaining 60%, our survey method may result in 25 candidate LBVs and B[e] stars in M31.

#### 4.2. Environments

Increasing samples of LBV and B[e] candidates will lead to better constraints on the progenitors and ages of these objects through study of their environments (see, e.g., St-Louis 1997). We will more extensively discuss the environments with the presentation of the WIYN 3.5 m imaging data (King et al. 1998). Here we briefly describe the environments as seen in the continuum and line images from the KPNO 0.9 m run. We note that the depth  $(m_B \sim 21)$  and resolution ( $\sim 2''$ ) of these images are not optimal, but they are sufficient to detect young stellar associations. We have also consulted the van den Bergh (1964) catalog of OB associations and indicate the association number (A). Wolf-Rayet stars are listed for the relevant associations that have been surveyed (Armandroff & Massey 1991). The sizes and distances stated are projected dimensions, which, given the inclination of M31, can be significantly smaller than the actual distances. To give some indication of the star formation activity in the region near the candidates we list the closest H II region that has an H $\alpha$  luminosity of the same order as the Orion Nebula ( $L_{H\alpha} \sim 10^{37}$ ) or larger (WB92). Note that the Orion Nebula is only a modest star-forming region. Figure 1 illustrates the H II regions near the candidates, although they are more easily visible in the larger maps seen in WB92. We also compare the heliocentric radial velocities of the candidates with that of the surrounding H I gas (Brinks & Shane 1984). We have included a discussion of the environment of the LBV Var A-1 And because we have images of it from the WB92 survey (it is within the H II region K569 of Fig. 2g of WB92; it can also be seen in Fig. 3 of Rosino & Bianchini 1973).

K370 is in the large OB association A38 and has a few fainter stars that are within a projected distance of about 20 pc. The nearest H II region is ~280 pc away (K405,  $L_{H\alpha} = 4.5 \times 10^{36}$  ergs s<sup>-1</sup>). K370's heliocentric radial velocity, -210 km s<sup>-1</sup>, falls within the observed range of H I velocities -175 through -305 km s<sup>-1</sup> at this projected position.

K350 appears to be on the edge of a diffuse H II region, K343, which has a luminosity of  $L_{\text{H}\alpha} = 1.1 \times 10^{37}$  ergs s<sup>-1</sup>. There is a fainter blue star within a projected distance of about 10 pc. K350 is within the OB association A32, which has a W-R star of type WC6-7 220 pc away. The radial velocity of K350, -247 km s<sup>-1</sup>, implies that the object has no radial space motion with respect to the H I gas that is observed between the velocities of -220 and -305 km s<sup>-1</sup> at this position.

K895 is ~110 pc from the H II region K896 ( $L_{H\alpha} = 1.4 \times 10^{36} \text{ ergs s}^{-1}$ ), and is 375 pc from the brighter H II region K915 ( $L_{H\alpha} = 2 \times 10^{37} \text{ ergs s}^{-1}$ ). There are no neighboring stars of comparable brightness. The nearest OB association, A102, is about 220 pc away. With a heliocentric radial velocity of 2 km s<sup>-1</sup>, K895 displays radial space motion of about 40 km s<sup>-1</sup> with respect to the spiral arm that is observed in the range -41 through -66 km s<sup>-1</sup>.

The H II region nearest to K411 is K418; it is ~75 pc away and has a brightness of ~ $3.7 \times 10^{36}$  ergs s<sup>-1</sup> in H $\alpha$ . There are no stars of brightness comparable to K411 visible in the vicinity. The nearest OB associations are about 100 pc away. With a heliocentric radial velocity of -7 km s<sup>-1</sup>, K411 has a minimum radial space velocity of about 43 km s<sup>-1</sup> with respect to that of the spiral arm, which is emitting at velocities of -50 km s<sup>-1</sup> through -270 km s<sup>-1</sup>.

K315a is on the edge of a large (diameter ~140 pc) and bright ( $L_{\rm H\alpha} = 7.4 \times 10^{37}$  ergs s<sup>-1</sup>) H II region. It is located within the OB association A10, which has one W-R star of type WC6-7 located about 50 pc from K315a. The H I gas at the projected position of K315a is seen between the velocities of -58 km s<sup>-1</sup> and -239 km s<sup>-1</sup>. K315a has a heliocentric radial velocity of -95 km s<sup>-1</sup>, which indicates that K315a appears to be in the same velocity space as the spiral arm.

K114a is within a diffuse and faint  $(L_{H\alpha} = 5.5 \times 10^{36} \text{ ergs} \text{ s}^{-1})$  H II region. There are no nearby stars of comparable brightness visible within 50 pc. Within 100 pc, four bright stars are found. The nearest associations are A58 and A59, whose outer boundaries are about 300 pc away. K114a, with a heliocentric radial velocity of  $-132 \text{ km s}^{-1}$ , displays no radial space motion with respect to the H I gas in the spiral arm seen to be emitting between  $-132 \text{ and } -264 \text{ km} \text{ s}^{-1}$ .

Var A-1 And is within a moderately bright H II region  $(L_{H\alpha} > 1.5 \times 10^{37} \text{ ergs s}^{-1})$ , K569, and the OB association OB A42. There are two W-R stars within this association of type WC6-7 that are located 154 and 357 pc away. Var A-1 has a dimmer companion less than 20 pc east and three bright redder stars within 100 pc. An arc of H $\alpha$  emission to the northeast of Var A-1 at a radial distance of 15 pc can be seen.

It is perhaps remarkable that none of the six stars are located in or near the centers of prominent H II regions. Sources such as K370 are so bright in H $\alpha$  that they would have been recognized easily unless they were to coincide with an even brighter peak of an H II region complex; such peaks are rather sparse. We are looking for embedded sources by obtaining spectra of the bright condensations in H Π regions that have low-[S Π] emission. We have obtained one spectrum for an embedded target. It shows the object not to be a candidate LBV. Results then so far support the notion that we are finding objects that are old enough to be no longer associated with young H II region complexes, which implies ages in excess of several million years. Our result is consistent with the  $\sim 6$  Myr that St-Louis (1997) finds for one LBV based on its proximity to an LMC cluster.

Several objects, in fact, are quite isolated. For example, K895 and K411 are not in OB associations, nor are they in H II regions. Several others are located within the broadly drawn boundaries of OB associations, but they have no clear concentration of OB stars or an H II region in the immediate neighborhood. The isolation issue is relevant to formation mechanisms as well as ages of these objects.

The isolated stars could be runaways or field stars formed in situ. With radial space velocities of ~40 km s<sup>-1</sup>, K895 and K411 are possibly runaway stars. A star with a space velocity of 40 km s<sup>-1</sup> relative to the surrounding medium will travel 200 pc in  $5 \times 10^6$  yr, which makes it possible that K895 and K411 are stars that have been ejected from nearby OB associations through a binary process (Gallagher 1989; Blaauw 1993). None of the other four objects show a significant difference between the observed heliocentric velocities and the spiral-arm heliocentric velocities, and therefore have probably strayed very little from their birth sites.

#### 5. CONCLUSION

High-resolution deep H $\alpha$  and [S II] images of nearby galaxies are very good ways to survey nearby galaxies to find candidate LBVs and B[e] stars. We have found five such objects in part of M31 and speculate that ~25 more might also be confirmed over the whole of the galaxy. We also find that most of the five sources appear to be isolated.

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