CLASSIFICATION OF O STARS IN THE YELLOW-GREEN: THE EXCITING STAR VES 735

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ABSTRACT

Acquiring data for spectral classification of heavily reddened stars using traditional criteria in the blue-violet region of the spectrum can be prohibitively time consuming using small to medium sized telescopes. One such star is the Vatican Observatory emission-line star VES 735, which we have found excites the H II region KR 140. In order to classify VES 735, we have constructed an atlas of stellar spectra of O stars in the yellow-green (4800–5420 Å). We calibrate spectral type versus the line ratio He I λ4922:He II λ5411, showing that this ratio should be useful for the classification of heavily reddened O stars associated with H II regions.

Application to VES 735 shows that the spectral type is O8.5. The absolute magnitude suggests luminosity class V. Comparison of the rate of emission of ionizing photons and the bolometric luminosity of VES 735, inferred from radio and infrared measurements of the KR 140 region, to recent stellar models gives consistent evidence for a main-sequence star of mass 25 M☉ and age less than a few million years with a covering factor 0.4–0.5 by the nebular material.

Spectra taken in the red (6500–6700 Å) show that the stellar Hα emission is double-peaked about the systemic velocity and slightly variable. Hβ is in absorption, so that the emission-line classification is "(e)". However, unlike the case of the more well-known O(e) star ζ Oph, the emission from VES 735 appears to be long-lived rather than episodic.

Key words: H II regions — stars: early-type — stars: fundamental parameters — stars: individual (VES 735)

1. INTRODUCTION

Accurate classification of OB stars associated with H II regions is important for the self-consistent modeling of the energetics. As part of our study of the isolated H II region KR 140 (Ballantyne, Martin, & Kerton 1999) we have recently completed a series of spectroscopic observations to classify its exciting star, VES 735 (α2000 = 23°20′53.37″, δ2000 = 61°7′9.82″). VES 735 was discovered and cataloged in a Vatican Observatory objective prism emission-line survey (Coyne & MacConnell 1983). Given its central association with an H II region (see Fig. 1 and § 3) and its emission-line characteristics, VES 735 has to be an OBe star, but until now its spectral classification has not been determined.

Due to the high level of reddening toward this star (V = 12.88, B = 14.41; D. Balam 1997, private communication) we were forced to find the temperature-related classification using an alternative helium line ratio, He I λ4922:He II λ5411 in the yellow-green spectral region. In § 2 we describe the atlas of spectra used to calibrate the spectral type versus this helium line ratio. This calibration should be useful for classification of faint O stars associated with H II regions; in § 2.2 we apply it to VES 735 in particular. In § 3 we consider the emission-line properties of the star. Photometry of the star is used in § 4 to obtain a luminosity class for the star. A detailed, multiwavelength study of the KR 140 H II region and associated infrared nebula is presented in another publication (Ballantyne et al. 1999). In § 5 the radio and infrared continuum measurements are summarized. We discuss how these might be used to investigate the rate of emission of ionizing photons and bolometric luminosity of the exciting star, respectively, with application to VES 735. Conclusions are presented in § 6.

2. ATLAS OF MK STANDARDS IN THE YELLOW-GREEN

Traditionally, MK classification of O stars is done in the blue-violet spectral region (3800–4900 Å). The ratio of the He I triplet line λ4471 (2 3 P–4 3 D) and the He II λ4541 (Pickering 4–9) line is used as the key temperature criterion (Morgan, Keenan, & Bellman 1943; Conti & Aeschauer 1971). The heavy reddening of VES 735 made obtaining adequate spectra (S/N ~ 300 in the blue-violet) prohibitive on the 1.9 m telescope at the David Dunlap Observatory (DDO; see Fig. 2), and so we decided to look for suitable helium line ratios further to the red.

One possibility involves the lines He I λ5876 (2 3 P–3 3 D) and He II λ5411 (Pickering 4–7); this line ratio corresponds very well with the spectral-type sequence (Walborn 1980). However, we show in § 3 that VES 735 is an O(e) star with double-peaked emission at Hβ throughout the time of our observations. Such stars can have He I λ5876 in emission (Conti & Leep 1974), and indeed we find that the corresponding singlet line He I λ6678 line (2 1 P–3 1 D) is slightly in emission. Therefore, since application of the calibration to VES 735 was our primary goal, we decided to use the line He I λ4922 (2 1 P–4 1 D), the singlet line corresponding to the λ4471 triplet line. Although this line is now slightly to the blue of λ5411, it is still possible to obtain spectra of adequate S/N.

Due to the location of these lines between the blue-violet and the red, there has been no work done on the systematics of the line ratio with spectral type; therefore, we needed to calibrate the line ratio directly using a series of stars of known spectral type. Stars used in the calibration of the helium line ratio are listed in Table 1 along with references.
for their MK classification. The stars observed initially were all taken from Walborn’s atlas of O star spectra (Walborn 1990). Stars were then chosen from the other sources listed in Table 1 to fill in gaps in spectral type coverage and to provide duplication at some of the spectral types. If there are two different published spectral types for a given star, the spectral types and sources are separated by a semicolon in Table 1. An O4 star, HD 46223, was also observed to illustrate the disappearance of He i λ4922 by that spectral type. Similarly, HD 22951 was observed to show He ii λ5411 disappearing by B0.5.

These stars were observed between 1996 October and 1997 December using a Cassegrain-mounted CCD spectrograph at DDO. All of the spectra have a dispersion of 32.5 Å mm\(^{-1}\) and a resolution of Δλ = 2 Å. The CCD data were reduced using standard IRAF procedures for the processing of stellar spectra. Spectra of stars that were observed more than once, including VES 735, were co-added after being brought to a common heliocentric radial velocity scale. The reduced spectra of the calibration stars are displayed rectified and on a common scale in Figure 3.

### 2.1. Calibration

To provide a calibration of the spectral type versus the He i λ4922:He ii λ5411 line ratio, the equivalent widths (W) of the λ5411 and λ4922 lines were first measured for all of the calibration stars, using a line-fitting program that fitted a Gaussian profile and a linear background simultaneously to the line and the surrounding continuum. Equivalent

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2 Kamper, K. 1996, DDO Observer’s Manual, http://www.astro.utoronto.ca/~kamper/ddo_man1.html
TABLE 1
He I λ4922:He II λ5411 CALIBRATION STARS

| Star  | \( \alpha_{2000} \) | \( \delta_{2000} \) | Spectral Type | Source          |
|-------|---------------------|---------------------|---------------|----------------|
| HD 46223 | 6 32 9.32         | 4 49 24.9         | O4 V; O5 V    | W90, M&K, MAT; C&L |
| HD 46150 | 6 31 55.53        | 4 56 34.5         | O5 V; O5.5 V  | W90, M&K, MAT; C&L |
| HD 199579 | 20 56 34.67       | 44 55 29.4        | O6 V; O6.5 III| MAT; C&L         |
| HD 54662 | 7 9 20.22         | -10 20 49.4       | O6.5 V; O7 V  | W73; C&L         |
| HD 47839 | 6 40 58.62        | 9 53 44.73        | O7 V; O8 III  | W90, M&K, MAT; C&L |
| HD 48099 | 6 41 59.2         | 6 20 42.73        | O7 V; O6.5 V  | W73; C&L         |
| HD 53975 | 7 6 35.87         | -12 23 38.11      | O7.5 V        | W73, C&L         |
| HD 48279 | 6 42 40.45        | 1 42 57.58        | O8 V          | W90, C&L         |
| HD 46149 | 6 31 52.54        | 5 1 59.4          | O8.5 V        | W73, C&L         |
| HD 214680 | 22 39 15.6        | 39 3 1.21         | O9 V; O8 III  | M&K; C&L         |
| HD 46202 | 6 32 10.48        | 4 58 0.1          | O9 V          | W90, J&M, MAT; C&L |
| HD 193322 | 20 18 6.92        | 40 43 55.77       | O9 V; O8.5 III| W73; C&L         |
| HD 34078 | 5 16 18.15        | 34 18 41.59       | O9.5 V        | J&M, C&L         |
| HD 36512 | 5 31 55.79        | -7 18 5.13        | B0 V          | W90, M&K         |
| HD 206183 | 21 38 26.2        | 56 58 25.58       | B0 V          | J&M              |
| HD 22951 | 3 42 22.5         | 33 57 54.31       | B0.5 V        | J&M              |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

Sources.—(W90) Walborn 1990; (M&K) Morgan & Keenan 1973; (MAT) Morgan et al. 1978; (C&L) Conti & Leep 1974; (W73) Walborn 1973; (J&M) Johnson & Morgan 1953.

widths obtained this way were compared with values obtained using an alternative technique where a linear background was fitted to the continuum and \( W \) was simply the integrated sum of the difference between the continuum and the data. The two techniques agreed to within 1% for all of the stars observed. The \( W \)-values and their statistical errors reported in Table 2 were obtained using the first technique.

In Figure 4 we show a plot of spectral type (SpT) versus the logarithm of the line ratio \( R = W_{4922}/W_{5411} \) for all of the calibration stars. In order to take into account uncertainties in the spectral classification, the equivalent width ratio for those stars with more than one published spectral type is plotted for each spectral type. These stars are indicated by the joined data points. The strong correlation \((r = 0.965)\) between log \( R \) and spectral type is evident. A least-squares fit was made to the data,

\[
\text{SpT} = (9.04 \pm 0.10) + (4.10 \pm 0.23) \log R ,
\]

and is shown in the figure as a solid line. In the next subsection we apply this calibration to our measurements of VES 735. Note that the choice of functional form does not fit the data.

TABLE 2

| Star  | \( W_{5411} \) (Å) | \( W_{4922} \) (Å) | \( R = W_{4922}/W_{5411} \) |
|-------|---------------------|---------------------|-----------------------------|
| HD 46150 | 0.900 \( \pm \) 0.018 | 0.134 \( \pm \) 0.014 | 0.149 \( \pm \) 0.016 |
| HD 199579 | 0.881 \( \pm \) 0.014 | 0.187 \( \pm \) 0.007 | 0.212 \( \pm \) 0.009 |
| HD 54662 | 0.931 \( \pm \) 0.017 | 0.220 \( \pm \) 0.011 | 0.236 \( \pm \) 0.021 |
| HD 47839 | 0.730 \( \pm \) 0.012 | 0.287 \( \pm \) 0.008 | 0.393 \( \pm \) 0.013 |
| HD 48099 | 0.832 \( \pm \) 0.015 | 0.189 \( \pm \) 0.017 | 0.227 \( \pm \) 0.013 |
| HD 53975 | 0.794 \( \pm \) 0.011 | 0.350 \( \pm \) 0.013 | 0.441 \( \pm \) 0.017 |
| HD 48279 | 0.799 \( \pm \) 0.021 | 0.539 \( \pm \) 0.023 | 0.675 \( \pm \) 0.034 |
| HD 46149 | 0.661 \( \pm \) 0.019 | 0.431 \( \pm \) 0.007 | 0.652 \( \pm \) 0.022 |
| HD 214680 | 0.640 \( \pm \) 0.013 | 0.492 \( \pm \) 0.011 | 0.769 \( \pm \) 0.023 |
| HD 46202 | 0.467 \( \pm \) 0.015 | 0.524 \( \pm \) 0.014 | 1.122 \( \pm \) 0.047 |
| HD 193322 | 0.536 \( \pm \) 0.017 | 0.507 \( \pm \) 0.017 | 0.946 \( \pm \) 0.044 |
| HD 34078 | 0.496 \( \pm \) 0.013 | 0.564 \( \pm \) 0.010 | 1.139 \( \pm \) 0.036 |
| HD 36512 | 0.372 \( \pm \) 0.008 | 0.635 \( \pm \) 0.012 | 1.707 \( \pm \) 0.049 |
| HD 206183 | 0.428 \( \pm \) 0.015 | 0.598 \( \pm \) 0.010 | 1.397 \( \pm \) 0.054 |
| VES 735 | 0.729 \( \pm \) 0.046 | 0.475 \( \pm \) 0.043 | 0.652 \( \pm \) 0.072 |

Fig. 3.—Atlas of OB stellar spectra in the yellow-green. Calibration stars used in this study are shown rectified and on a common scale (with offsets of 0.3 units between spectra). The O4 and B0.5 stars are included to illustrate the disappearance of the He I λ4922 and He II λ5411 lines, respectively.
Spectral type (O subtypes) vs. log of the ratio of the equivalent widths, Spectral Type 10 refers to B0 stars. Stars with more than one published spectral type are denoted by the joined data points. The linear least-squares fit to the data is shown. The vertical lines denote the measured $R$ with its standard error for VES 735.

The vertical solid and dashed lines shown in Figure 4 represent our measurement of the line ratio $R$ and its standard error for VES 735 (see Table 2). Using equation (1) we found $SpT = 8.3$. Combining the uncertainty in our measurement of $R$ for VES 735 and the standard errors from the calibration, we estimate the total uncertainty in spectral type is $\pm 0.5$. As noted, in this temperature range spectral types are usually given with only 0.5 subdivisions; we conclude that VES 735 is an O8.5 star, with O8 and O9 being possibilities too. Figure 6 provides a comparison of the VES 735 spectrum with those of the O7.5, O8, and O8.5 calibration stars. Since VES 735 is rapidly rotating (see § 3) the comparison star spectra have been artificially broadened to simulate the effect of rotation on the general appearance of the spectrum.

In addition to the yellow-green spectra obtained for classification purposes we obtained H$\alpha$ spectra (6500–6700 Å) of VES 735 in 1996 October, 1997 January, and 1997 December at DDO. The spectra were obtained using the Cassegrain-mounted CCD spectrograph with a dispersion of 10.2 Å mm$^{-1}$ and an instrumental resolution of $\Delta\lambda = 0.5$ Å. Spectra at similar dispersion and a resolution of 0.7 Å were also obtained in 1997 September at the Dominion Astrophysical Observatory (DAO). A series of red spectra (some co-added over several days) of the star are shown in Figure 7 with notable features highlighted. A spectrum of the star BD+61 411 (spectral type O8e) is shown for comparison.

The initial spectrum, in 1996 October, was obtained to confirm the emission-line character of the star as implied by its discovery in the Vatican emission-line survey and to demonstrate the association of the star with the surrounding nebulosity as will be discussed. The later spectra from both DDO and DAO were obtained in order to monitor the longevity and/or variability of the observed emission.

The most obvious feature visible in the red spectrum is the double-peaked H$\alpha$ emission. As in Be stars, this shape is probably due to a rotating disk or shell of material around the star (Conti & Leep 1974). The two peaks are separated by about 400 km s$^{-1}$ and have shown variability in peak separation and height over the time period of our observations (see Fig. 8). From the extent of the emission the
rotating gas has $v \sin i \approx 400$ km s$^{-1}$, corresponding to an (inner) orbital distance of about $2 \times 10^{12}$ cm or about $4R_{\text{star}}$. Accounting for an underlying absorption $W$-value of about 2.6 Å (estimated from BD + 61 411) the total $W$ of the emission is 4.1 Å.

Note also that Hβ in VES 735 is much weaker in absorption than in the calibration stars in Figure 6, and so it is probably partially filled in with emission. The implied $W$-value of the Hβ emission is about 1.5 Å.

The 1997 January spectrum extends slightly redder, to include coverage of entire He $\text{i}$ 6678 line to see if it would be useful for classification purposes (see Groppi & Hansen 1996 for digital spectra of dwarf O stars in the red). The spectrum shows that the He $\text{i}$ 6678 line is being filled in by emission and therefore would not be useful. The implied $W$-value of the emission is about 0.2 Å.

Since we do not see any evidence for emission in the other lines of the Balmer series, VES 735 is an O(e) star, using the notation of Conti & Leep (1974) to denote visible emission in the Balmer series only at Hz. Oe and O(e) stars are the higher mass counterparts of the more common and well-studied Be stars (Frost & Conti 1976). The double-peak nature of the observed Hβ emission is similar to that observed in the most well-known example of an O(e) star, ζ Oph [O9 V(e); Niemelä & Méndez 1974]. Unlike VES 735, the Hz emission from ζ Oph has been very episodic, with emission outbursts lasting only a few months and years passing between successive episodes (Niemelä & Méndez 1974; Ebbets 1981). Incidentally, spectra taken of ζ Oph at DDO in 1997 June showed no visible Hz emission.

From the Hz and Hβ emission-line $W$-values, and the fluxes $F_i$ of the stellar continuum at these wavelengths, the Balmer decrement $D_{43} = (WF_\lambda)/(WF_\psi) = 0.9 \pm 0.1$; the uncertainty includes the measurement error and the uncertainty in the effective temperature ($T_{\text{eff}}$) and the shape of the stellar atmosphere flux distribution (relative $F\lambda$). This flat (even inverted) decrement can be compared to values from a study of Be stars by Dachs, Rohe, & Loose (1990). They find that the lowest decrements occur for stars with relatively weak emission and for the early spectral types; VES 735 appears to fit these trends, though it has a flatter decrement than found in the Be stars (the lowest was 1.2). Their interpretation is that flat decrements like this arise due to optical depth effects in circumstellar environments that are abnormally dense and compact. The circumstellar line-emitting plasma also has continuous emission, most readily detected in the near-infrared. Their interpretation is supported by the measured low ratio of line to continuous emission in Be stars with a low decrement.

Note that if the optical light is contaminated by the continuous emission of the circumstellar gas (perhaps 10%–20% at $V$), then the measured light is brighter and redder than the photosphere alone. Both effects would make the measured $M_V$ too bright (negative), by perhaps as much as 0.3 mag.

The most common theory to explain the Oe and Be star phenomenon has to do with mass loss from young stars. Most Oe and Be stars are rotating very rapidly and undergo periodic mass loss by some unknown mechanism (e.g., Kambe, Ando, & Hirata 1993; Howarth et al. 1993). A simple measurement of the λ4922 line, assuming that it is purely rotationally broadened, gives $v \sin i \approx 300$ km s$^{-1}$ for VES 735. Material ejected from the rapidly rotating star then orbits the star in a disk causing the observed emission-line characteristics. Winds from the star can eventually disperse the orbiting material and cause the emission features to fade and disappear (Ebbets 1981). Further monitoring of this interesting star in the Hz region would be of interest to see if the apparently long-lived emission persists.

An alternative to consider is that VES 735 might be a higher mass equivalent of a Herbig Be star, a very young star with a remnant disk of material from its formation (Walborn 1997). However, the likely evolutionary age of $3 \times 10^5$ yr for the KR 140 H II region argues against the star being extremely young (Ballantyne et al. 1999).
3.1. Effect on Our Spectral Classification

Since we know that VES 735 is an emission-line star, of more concern to us are any possible systematic errors in the measurement of $W_{\lambda 4922}$ caused by the filling in of the He I absorption line. If there is such contamination, then the line will appear to be too weak compared to the He II $\lambda 5411$ line for which we do not expect any filling in, and we will determine too early a spectral type for the star. To investigate this issue we plotted separately spectral type versus $W_{\lambda 4922}$ and $W_{\lambda 5411}$ (see Figs. 9 and 10). Linear trends are obvious ($r = 0.95$ and $r = -0.92$, respectively), and in both cases least-squares fits to the data were made:

$$\text{SpT} = (4.82 \pm 0.03) + (7.92 \pm 0.56)W_{\lambda 4922} \quad \text{(2)}$$

$$\text{SpT} = (12.80 \pm 0.41) - (7.08 \pm 0.58)W_{\lambda 5411} \quad \text{(3)}$$

The vertical solid and dashed lines represent the measured values of $W$ for VES 735 and the standard error. Using equations (2) and (3) we determine spectral types for VES 735 of O8.5 and O7.5, respectively, each $\pm 1$ spectral type; note that the type based on He I $\lambda 4922$ is later if anything. Both are consistent with the spectral type determined using equation (1). We conclude that filling in of the He I $\lambda 4922$ line is not a significant factor in our spectral classification of VES 735.

4. VES 735—Luminosity Class

4.1. Distance and Absolute Magnitude

During the 1996 October and 1997 January observing sessions at DDO we also obtained red spectra of BD +61 411, which excites the neighboring optical nebula IC 1795. Sharp nebular lines of H$\alpha$ detected on this spectrum and that of VES 735 (the KR 140 nebulosity) were used to determine the differential radial velocity of the two nebulae (the nebular lines are not visible in the "sky" subtracted spectra presented here). The velocity of IC 1795 is known from both H$\alpha$ and radio recombination lines to be $-46 \pm 2.1 \text{ km s}^{-1}$ (Courtes et al. 1966; Georgelin & Georgelin 1976). From this, the velocity of the KR 140 ionized gas was determined to be $-46 \pm 2.1 \text{ km s}^{-1}$. This is the same as the velocity of another nearby ($\sim 1'$) nebula IC 1805 that from photometric studies of its star cluster (Georgelin & Georgelin 1976) is known to be at a distance $d = 2.3 \pm 0.3$ kpc; the error estimate is based upon the scatter between various published distance measurements (see Leisawitz 1988). We adopt this as the distance to KR 140. A differential velocity of $+2.0 \pm 2.2 \text{ km s}^{-1}$ was measured between the nebular lines and the center of the stellar H$\alpha$ emission of VES 735, consistent at least with a close association of VES 735 with KR 140. Given also the central position of VES 735 in the nebula (Fig. 1), we therefore assume the same distance.

Photometry of VES 735 in the $B$ and $V$ bands was obtained for us at DAO: $V = 12.88 \pm 0.01$, $(B - V) = 1.53 \pm 0.02$ (D. Balam 1997, private communication). Using $(B - V)_0 = -0.31$ (the intrinsic colors of O and very early B stars do not vary significantly, Johnson 1967) and ratio of total to selective extinction $R_V = 3.1 \pm 0.1$ we obtain a value for the total $V$ band extinction, $A_V = 5.7 \pm 0.2$. Applying the usual distance modulus equation we find $M_V = -4.6 \pm 0.2$ with an additional $0.28$ mag from the uncertainty in distance. As noted in § 3, this might be as low as $M_V = -4.3$ if there is contamination by circumstellar continuous emission.

In Table 3 we summarize values of $M_V$ for O8.5 V and O8.5 III stars from various sources. Based upon our measurement of $M_V$, and given this spectral type, VES 735 is luminosity class V.

4.2. Checks on the Extinction

An H$\alpha$ image of KR 140 was obtained for us at the Observatoire du Mont Megantic (Fig. 11; Joncas 1997). This faint nebulosity is barely visible on the digitized red POSS plate, consistent with a threshold in emission measure $E$ of approximately $100 \text{ cm}^{-6} \text{ pc}$ (van Buren 1996). We also have a 1420 MHz continuum observation of the region at lower resolution (1'; Fig. 1; Ballantyne et al. 1999). We rebinned our radio image of the H$\alpha$ region to the pixel

| Source            | Class V | Class III |
|-------------------|---------|-----------|
| Vacca et al. 1996 | -4.55   | -5.52     |
| Panagia 1973      | -4.44   | -5.5      |
| Osterbrock 1974   | -5.0    | ...       |

TABLE 3

$M_V$ for O8.5 Stars
size of the Hβ image (1.6). Then, after removing point sources from the Hβ image, we used

$$A_V = \frac{A_{H\alpha}}{0.82} \cdot \frac{2.5}{0.82} \log \left( \frac{E_{1420}}{E_{H\alpha}} \right)$$

(4)
on a pixel-by-pixel basis to construct an extinction map for the region. Contours of $A_V$ are shown in Figure 11. Depending upon the background we chose to subtract from the radio continuum image we obtained a value of $A_V = 5.8 \pm 0.2$ near VES 735.

We were also able to use the strong diffuse interstellar bands (DIBs) at 4430 and 6613 Å as another independent check on the amount of reddening and extinction toward VES 735. Although a few other DIBs were tentatively identified in our spectra of VES 735, from the catalog of Jenniskens & Désert (1994), they could not be measured precisely enough to be useful.

For the λ4430 DIB, a correlation exists between percent-age central depth, $A_c$, and $E_{b-v}$ (Snow, York, & Welty 1977): $A_c = 7.02 E_{b-v} + 2.74$, with rms dispersion $\sigma = 1.65$. In the VES 735 blue spectrum we measured $A_c = 15$, so that $E_{b-v} = 1.75$ and $A_V = 5.4$, using $R_V = 3.1$. For the λ6613 feature we measured $W_{6613} = 0.40$; using the average $W/E_{b-v} = 0.231$ reported by Jenniskens & Désert (1994), this corresponds to $A_V = 5.4$. These results all show that the value derived for $A_V$ via photometry is reasonable.

5. VES 735—IONIZING PHOTONS AND BOLOMETRIC LUMINOSITY

As described below, radio continuum observations of H II regions can provide a measurement of the total flux of ionizing photons, $Q(H^0)$, of the exciting star(s). We show how, in theory, the combination of the observables $Q(H^0)$ and $M_V$ can provide an independent confirmation of both the luminosity and the temperature classification of an OB star.

If there were other undetected O stars then the $Q(H^0)$ measured will be related to the combined output of the stars and the technique clearly cannot be used to classify the visible star. Similarly, the infrared reemission by dust and polycyclic aromatic hydrocarbons (PAHs) constrains the total luminosity. We illustrate some of the uncertainties encountered in an actual application to VES 735.

5.1. The Radio Flux—$Q(H^0)$ Relation

$Q(H^0)$ is related to the observed radio continuum flux ($F_r$) by

$$fQ(H^0) = \frac{\alpha_B F_r d^2}{j_v},$$

(5)

where $\alpha_B$ is the case B recombination coefficient of H$^+$ ($3.27 \times 10^{-13}$ cm$^{-3}$ s$^{-1}$ at 7500 K; Storey & Hummer 1995), $j_v$ is the free-free emissivity for H$^+$ ($3.45 \times 10^{-40}$ ergs cm$^{-3}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ at 1420 MHz and 7500 K; after Lang 1980) and $f$ is the result of several correction factors to be described. Our measured value of $F_r$(1420 MHz) = 2.35 ± 0.05 Jy (Ballantyne et al. 1999) then yields $fQ(H^0) = (1.1 \pm 0.2) \times 10^{48}$ s$^{-1}$, or log $[fQ(H^0)] = 48.05 \pm 0.1$.

A fraction of the star’s ionizing photons might escape from the H II region, making the observed $F_r$ smaller (without affecting $M_V$), if the nebula is not ionized in the radial direction and/or the covering factor is less than unity. This can be described by a factor $f_{\text{esc}} \leq 1$.

Dust in the nebula competes with the gas for ionizing photons, producing a factor $f_{\text{dust}} \leq 1$. As described by Botteri et al. 1998, the effectiveness of dust depends on the optical depth to ionizing photons (hence column density and shape of the absorption curve) across the ionized volume, which in turn depends on the ionization parameter (basically the ratio of the ionizing photon flux to the electron density). We have used version 90.04 of the spectral synthesis code CLOUDY (Ferland et al. 1998) to model the specific case of KR 140 illuminated by VES 735, matching both the flux and spatial distribution of surface brightness in the radio and infrared (Ballantyne et al. 1999). We estimate that log ($f_{\text{dust}}$) $\sim -0.1$ for dust like that in the diffuse interstellar medium, where the absorption in the far ultraviolet is much larger than in the optical; for dust like that found in dark clouds, where the absorption increase into the ultraviolet is less pronounced, the competition for ionizing photons is less efficient and log ($f_{\text{dust}}$) $\sim -0.03$.

Finally, a factor $f_{\text{complex}}$ is needed to account for the fact that a nebula is more complex than assumed by this approximation based on pure H at constant temperature. Helium is the next most relevant element here. For a relatively low-temperature star like VES 735 and a relatively low-density nebula like KR 140, most of the ionizing photons expended on ionizing He ultimately produce H ionization as well (Osterbrock 1989), and so the total ionization rate of H is not much affected (nor is the total emission of Hβ). However, He is singly ionized in part of the volume, and where present, He$^+$ increases the effective free-free emissivity (the effect over the whole nebula KR 140 might amount to a factor 1.06 [0.025 dex]). Finally, $\alpha_B$ and $j_v$ have different temperature dependences and the temperature is not constant in a nebula; but the effect on the ratio is probably a few percent or less.

In general is hard to decouple the contributions $f_{\text{dust}}$ and $f_{\text{complex}}$ entirely as they depend on and affect nebular struc-
ture. However, their joint effect $f_{\text{model}}$ can be estimated using model calculations. Our best estimate from models that reproduce the size of the nebula and the radio and infrared flux is $\log (f_{\text{model}}) \sim -0.04 \pm 0.04$.

Hence, $\log [f_{\text{ad}} Q(\text{H}^0)] = 48.09 \pm 0.11$. Paired with the observed $M_V$, this is plotted in Figure 12, which has axes oriented like a Hertzsprung-Russell diagram. The error bars on the point (a diamond symbol) represent those not related to the distance to VES 735. Since distance enters into the calculation of both $M_V$ and $Q(\text{H}^0)$, we indicate the effect of either increasing or decreasing the distance to the star by two arrows (to the upper left and lower right, respectively). The length of the arrows represents a distance change of $\pm 300$ pc, the estimated error, which affects $\log [Q(\text{H}^0)]$ by about $\pm 0.11$ dex.

5.2. The Infrared Flux—$L_{\text{bol}}$ Relation

Dust in and surrounding an H II region absorbs radiation, both the starlight directly and the diffuse (largely line) emission. Measuring the integrated dust radiation in the infrared, $f_{\text{ad}}$, gives an estimate of the total, $L_{\text{bol}}$, reduced by the fraction $f_{\text{ad}}$. The criteria for $f_{\text{ad}}$ approaching unity are that in the radial direction through the region actually being measured the absorption optical depth be significant, particularly in the ultraviolet where most of the energy is, and that the covering factor be large. Therefore, $f_{\text{ad}}$ is akin to $f_{\text{cd}}$, though as alluded to in § 5.1 most of the absorption by dust occurs outside the ionized volume; with material with adequate radial extent, probably the case here, they are both equivalent to the covering factor. From models for which $f_{\text{cd}} = 1$, we find that $\log (L_{\text{ad}}/L_{\text{bol}}) \sim -0.1$ because a small fraction of the nebular gaseous reemission is at long enough wavelengths to be hard to absorb fully.

From HiRes images made from IRAS data, supplemented by the modeling described which allows us to account for the unobserved emission at longer wavelengths, we estimate that $\log (f_{\text{cd}} L_{\text{bol}}/L_\odot) = 4.55 \pm 0.1$ (Ballantyne et al. 1999).

Fig. 12.—$M_V$ vs. $\log [Q(\text{H}^0)]$ from various stellar model predictions. Values deduced for VES 735 plotted as a diamond, with error bars denoting errors not associated with the distance; effect of increasing (decreasing) the distance by 300 pc shown by the arrow to the upper left (lower right). Models from Panagia (1973) and Vacca et al. (1996) are plotted at half-spectral-type intervals from O5 to B0. Models from Osterbrock (1974) are shown at full-spectral-type intervals from O5 to O9, then at half-spectral-type intervals. The O8.5 models are circled. The right arrow from the O8.5 $V$ model of Vacca et al. (1996) estimates the combined effect of a lower effective temperature calibration and using the wind-blanked atmospheres of Schaerer & de Koter (1997) (see § 5.4).

5.3. Stellar Predictions of $M_V$ and $L_{\text{bol}}$ versus $\log [Q(\text{H}^0)]$

In Figure 12 we have plotted predictions based on OB star models from Vacca, Garmany, & Shull (1996), Osterbrock (1974) (reproduced in Osterbrock 1989), and Panagia (1973). The O8.5 predictions for each are circled. Even with precise models (and a large covering factor) it is readily apparent that either $M_V$ or $Q(\text{H}^0)$ alone is insufficient to obtain a full spectral classification; a cooler giant star can have the same $M_V$ or $Q(\text{H}^0)$ as a hotter main-sequence star. For example, in the Vacca et al. (1996) model, $M_V$($V5$) = $M_V$(B0.5 III), and in the Panagia (1973) model, $\log (Q(\text{H}^0))$(O8.5) = $\log (Q(\text{H}^0))$(O9.5 III). But by using both $M_V$ and $\log [Q(\text{H}^0)]$ one should, in principle, be able to remove this degeneracy and obtain an independent estimate of the spectral classification.

However, there are clearly significant disagreements between models. They arise from different calibrations of $T_{\text{eff}}$ versus spectral type, different $M_V$ calibrations versus spectral type, and different stellar atmosphere models used in predicting the continuum (see Vacca et al. 1996 for a discussion of these differences and the intrinsic uncertainties involved). Systematic differences lead to displacement and stretching (contraction) of the loci in a diagram like Figure 12. There is also cosmic scatter of both $T_{\text{eff}}$ ($\pm 1700$ K) and $M_V$ ($\pm 0.67$ magnitudes) at a given spectral type (Vacca et al. 1996) to be considered along with the uncertainty of the calibration (average value). At O8.5 $V$, an uncertainty of $1700$ K would correspond to an error in $\log [Q(\text{H}^0)]$ of 0.17 dex.

Figure 13 has loci based on the predicted $L_{\text{bol}}$ from Vacca et al. (1996) and Panagia (1973). Also plotted are a few of the evolutionary models, with wind-blanked atmospheres, from Schaerer & de Koter (1997). Model B1 is a for a 25 $M_\odot$ star at age $2.8 \times 10^4$ yr. B2 follows the evolution on the main sequence to age $2.6 \times 10^6$ yr, while B3 corresponds to a cooler subgiant at age $4.8 \times 10^6$ yr.
5.4. Discussion

The Osterbrock (1974) model in Figure 12 suggests a classification O9–9.5 V for VES 735. However, our spectroscopic observations are not consistent with such a late O spectral type; nor are these models based on the most current calibrations and atmospheres.

For the observed $M_V$, the Panagia (1973) models place the star near O7.5, which is perhaps too early. More importantly, this has the implication that KR 140 is far from being ionization bound. The ring-shaped appearance of the radio nebula, which looks like the projection of a somewhat broken thick shell (Fig. 1). If instead one starts with the spectral type O8.5 V, then $\log (f_c) \approx -0.36$ and the observed $M_V$ is a bit bright, perhaps overestimated because of continuous emission from the circumstellar plasma ($\gamma$ 3).

For the observed $M_V$, the Vacca et al. (1996) models place the star at O8.5 V, but again with a very small covering factor ($\log (f_c) \sim -0.6$). There are two reasons that the Vacca et al. (1996) models might have overestimated $[\log (f_c)]$. First, the simple linear form of their calibration of $T_{\text{eff}}$ versus spectral type, intended to describe the trend over the whole range of OB stars, appears to overestimate the actual $T_{\text{eff}}$ for stars near O8.5 V by typically 1500 K. This would bring the scale closer to that adopted by Panagia (1973) and Leitherer (1990), whose values of $T_{\text{eff}}$ and $[\log (f_c)]$ near O8.5 V agree well. If so, then $[\log (f_c)]$ should move 0.15 dex to the right in Figure 12.

Second, more recent stellar atmosphere models that include wind blanketing have significant changes in the ionizing continuum at a given $T_{\text{eff}}$ (Schaerer & de Koter 1997). Specifically, near O8.5 V, $[\log (f_c)]$ is lowered by 0.1 dex, moving the prediction even further to the right to 48.47 as indicated by the arrow in Figure 12. While this is closer to the observed $[\log (f_c)]$, it still seems that $f_c$ is considerably less than unity ($\log (f_c) \sim -0.38$).

In Figure 13 we find evidence that $f_{\text{cl}}$ is also low, with a value consistent with $f_c$. Accounting for a covering factor of 0.4–0.5 would move the observed data point up by 0.3–0.4 dex to near the O8.5 V model of Panagia (1973) and B1 and B2 models of Schaerer & de Koter (1997). Matching the Vacca et al. (1996) O8.5 V model would require an even lower covering factor, which the geometrical evidence suggests is unlikely. However, if the Vacca et al. model were modified as described above, it would move closer to the B2 model. In the context of the Schaerer & de Koter (1997) models, and the deduced covering factor, VES 735 is a 25 $M_\odot$ main-sequence O star with an age less than a few million years.

6. Conclusions

Calibration of the He I λ4922:He II λ5411 line ratio using stars of known spectral type has allowed us to classify the heavily reddened star VES 735 as O8.5. The atlas of stellar spectra in the yellow-green along with the helium line calibration presented in this paper should be useful for other studies of highly reddened O stars, when obtaining reasonable classification spectra in the blue is prohibitive.

Photometry of VES 735 and spectra taken in the Hα region provided additional information on the luminosity and emission characteristics: VES 735 is an O8.5 V(e) star. This direct identification of the spectral type is useful in our modeling of the energetics of the surrounding H II region KR 140 (Ballantyne et al. 1999). Likewise, the modeling assists in assessing the ionizing luminosity and bolometric luminosity from the radio and infrared observations. There is consistent evidence from comparing these luminosities with the predictions of recent stellar models that VES 735 is a main-sequence star of mass 25 $M_\odot$ and age less than a few million years with a covering factor 0.4–0.5 by the nebular material. The Hα emission of this star appears to be quite long lived compared with the O(e) star ζ Oph and continued monitoring of its emission would be worthwhile.

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