Chapter 4

The Optical Classification-Resolution Spectroscopic Survey

Following our molecular and imaging surveys, we were able to obtain classification-resolution spectra for at least some of the stars projected onto the dark clouds defined by Ae/Be stars, in every region in our sample. With spectra, we can assign luminosity classes and spectral types which, in combination with the information derived from our optical imaging, allows us to determine photospheric temperatures and colors and thus to individually deredden stars and accurately place them in an HR diagram. From the HR diagram we can then estimate stellar masses and ages, based on comparison to pre-main sequence evolutionary tracks. We would like to perform this exercise for as many of the optically visible sources as possible in each region. Since our goal is the determination of composite stellar mass spectra, if we can assess the characteristic age of an aggregate based on traditional optical HR diagram techniques, we can then apply the method described in Chapter 7 to deredden the embedded populations and thus estimate masses for *all* sources detected to the limits of our deep infrared images. In this Chapter, we first justify our approach to obtaining classification spectra, then describe the data acquisition and reduction, and, finally, review our method of spectral classification.

The wavelength range over which we have obtained spectra encompasses the R-I color index, that which we use to determine stellar extinction values (see Chapter 8). Classifying spectra in the R-,I-band region, as opposed to the "classical MK region" ($\approx 4500 - 5500\ \AA$), is advantageous in sites of on-going star

formation for a variety of reasons. First, since the extinction at I-band is approximately 60% of its value at V-band, the effects of foreground interstellar and local molecular core obscuration are decreased by moving to longer wavelengths. Second, typical V-I colors range from 0.5-3.5 mag for our program stars; thus greater signal-to-noise spectra can be obtained at longer wavelengths as we sample the fainter, later type stars nearest as possible to the wavelength of their peak emission. Third, the blue continuum excesses produced by boundary layers in well-studied young star-plus-accretion-disk systems are known to veil (fill-in) photospheric absorption features; moving to longer wavelengths minimizes the possibility of contamination by such boundary layer emission.

Targets for spectroscopy were selected in two different manners, depending on the type of run (see below). In the cases where multi-object techniques were used, targets were selected purely on the basis of maximizing the total number of spectra obtained per CCD exposure. In the case where single-slit techniques were used, targets were selected primarily by brightness and by the presence of near-infrared excess emission in some cases.

4.1 Observations and Extraction of Stellar Spectra

Spectra were obtained during several runs with 3 different instruments: the Multiple Mirror Telescope and REDSPEC slit spectrograph, the Kitt Peak RC spectrograph in longslit and multislit modes, and the Kitt Peak fiber-fed HYDRA multi-object spectrograph. The spectral resolutions range from $R \approx 500 - 1500$ for these data.

In all cases, the images were processed with IRAF first by subtracting the bias voltage from the original CCD frames. For the single-slit and multi-slit data, flat field images which compensate both for pixel-to-pixel variations and for the slit function were created with APNORMALIZE and applied to the data.

One-dimensional spectra were extracted using APALL and wavelength calibration was established from exposures of He-Ne-Ar or Th-Ar (dependent upon the run) comparison lamps taken immediately following the target exposures. For the HYDRA data, the frames were first corrected for scattered light using the task APSCATTER and then DOHYDRA, a front-end program for aperture extraction of CCD frames containing multiple spectra, was used to extract the spectra, flat-field the individual fibers, correct for fiber-to-fiber response differences, and wavelength calibrate using exposures of a Th-Ar comparison lamp obtained for each fiber configuration. Sky subtraction was performed for both the slit and the fiber data during the extraction process, but we note that it is less accurate in the case of the fiber data (particularly in regions of heavy nebulosity) as "sky" can not be defined adjacent to the target spectrum as it can in the case of slit spectra.

Following spectral extraction, the data were post-processed before classification (in some cases) by smoothing over a single resolution element and normalizing to unity. Low signal-to-noise spectra and spectra of M stars (with broad molecular absorption features) were not normalized.

4.2 Quantitative Spectral Classification

The wavelength range covered by our observations includes the TiO ($\lambda\lambda$5847-6058, 6080-6390, 6651-6852, 7053-7270, 7666-7861, 8206-8569, 8860-8937 Å), VO ($\lambda\lambda$7334-7534, 7851-7973, 8521-8668 Å), CN (λ7878-8068 Å), and CaH (λ6386 Å) bands; the upper Paschen series and the Paschen jump; the Ca II triplet ($\lambda\lambda$8498, 8542, 8662 Å); O I lines ($\lambda\lambda$7774, 8446 Å); Hα (λ6563 Å); the Ca I /Fe I blend (λ6497 Å); Fe II lines (λ6242 Å blend, weak λ6456 Å); Ca I lines ($\lambda\lambda$6122, 6162 Å); the Mn I /Fe I blend (λ6015 Å); the Na I line (λ5893 Å , but not trustworthy for classification in star-forming regions because of a significant interstellar contribution); He I ($\lambda\lambda$5876, 6678, 7065 Å)

and He II line (5411 Å); and the Mg I /MgH blend (λ5180 Å). These lines can be used as temperature indicators. A few indicators of luminosity (CaH λ6975, Na λ8190, MgH λ5211, the Ca II triplet, and several Fe and Ti features) are also present and enable discrimination of of heavily-reddened low mass pre-main sequence stars from foreground dwarfs.

Lines in this spectral regime frequently produced in emission by young stars, are those of Hα , the Paschen lines, the Ca II triplet, the He I lines, the [O I] lines ($\lambda\lambda$6300, 6360 Å), the [S II] line ($\lambda\lambda$6716, 6731 Å), the Na I D lines, and an abundance of both permitted and forbidden Fe lines.

Spectral classification was done by comparison of our standard and program spectra to the standard sequences established over these wavelength regimes by Allen & Strom (1995), Kirkpatrick, Henry, & McCarthy (1991), and Jacoby, Hunter, & Christian (1984). For stars not severely affected by accretion processes, spectral typing can be accomplished fairly straightfowardly in this spectral regime. The errors are a function of spectral type and are discussed below.

O and B stars can be classified according to the strengths and ratios of He II and He I lines. The red He II line disappears by B0 while the red He I lines disappear by A0. A and F stars can be classified using the upper Paschen lines, the Ca I lines, the O I lines, and, to some extent, the Na I D lines; Na I and Ca I both increase in strength towards later spectral types while O I , Ca II , and Paschen strengths decrease. G and K stars can be classified using the Ca I lines, Hα , and the metallic blends at $\lambda\lambda$6015, 6497 Å . Late K and M stars can be classified quite successfully using the relative depths of the TiO, CN, VO and CaH molecular bands. In principle, Hα can also be used as a spectral type indicator for stars not affected by emission processes.

The spectra were first ordered into approximate spectral type bins according to the above criteria. Next, a quantitative depth-of-feature analysis was employed,

similar to that discussed by O'Connell (1973). The goal of a quantitative classification scheme is to obtain a numerical estimate of the strength of an absorption feature which is independent both of reddening and of the signal-to-noise ratio of the spectrum. Feature indicies are defined by measuring the flux deviation due to line absorption, from the continuum expected when interpolating between two nearby "side band" wavelength regimes. The side bands for each feature are chosen to be free of other absorption lines at the stellar temperature and of the emission lines typically seen in young stellar objects. A spectral index is given by the ratio of the flux measured at the central wavelength (λ_2) to the flux predicted from interpolation from the two side bands (λ_1 and λ_3) – simply understood as just $y_2/(y_1 + m\Delta x)$ – and converted into magnitudes, or

$$I = -2.5 \times log \frac{F_{\lambda_2}}{F_{\lambda_1} + (F_{\lambda_3} - F_{\lambda_1})/(\lambda_3 - \lambda_1) \times (\lambda_2 - \lambda_1)}.$$

Experimentation with artificially reddened standard-star spectra shows that this definition of an absorption index is insensitive at the level of $|dI/dA_v| \lesssim 0.005$ to the amount of reddening, as well as to the shape of the reddening law. In principal, this definition also should be independent of signal-to-noise (to within reason), as long as the side bands are chosen to be 1) nearby, in the case that signal-to-noise varies with wavelength and 2) sufficiently broad in bandpass, so that a good estimate of the mean continuum can be obtained.

For our purposes, we uniformly chose the bandpasses to be 30 $\mathring{A}$ wide for both the central and side bands. The assigned central and side band wavelengths are given in Table 4.1 and have been shifted in a few cases from their ideal locations in order to avoid spectral regions often contaminated by strong nebular emission lines (in case of poor sky subtraction). To assess the behavior of these indicies with spectral type, we first derived the indicies for the grid of standard stars presented by Allen & Strom (1995) supplemented with our own standards; these data were taken with the same telescope and instrument, and with an approximately

identical spectrograph setup, as were our program stars. They should, therefore, provide accurate calibration of the feature indicies.

Next, we compared our program stars to the standard stars, and derived quantitative spectral types from plots of one feature index versus another. For M stars the TiO λ6760 *vs.* TiO λ7100 and the TiO λ7800 *vs.* TiO λ7100 planes are the most useful for classification; for F2-K7 stars the Ca I λ6162 *vs.* Na I λ5892 plane is most useful; and for A0-G0 stars the Ca I λ6162 *vs.* Mg I λ5175 plane is most useful. After assigning preliminary spectral types using the quantitative technique, individual spectra were examined amidst a grid of standards in order to verify the quantitative spectral types. In general the quantitative technique works quite well and is more trustworthy than by-eye examination, particularly in cases of extremely reddened late-type stars.

We estimate that errors in the assigned spectral types are lowest ($\pm$1 subclass) for stars K7 and later, where spectral classification is relatively straightforward in the red spectral region, and highest ($\pm$1/2 class) for F and G stars where red spectral classification is most difficult. Propogated formal errors are discussed in Chapter 8 where we use our spectral types to construct HR diagrams. We also note that not all of our spectra are classify-able, as several of the Ae/Be regions contain so-called continuum - plus - emission sources, which lack photospheric absorption features. For this reason, we suspect that some of the spectral types derived using the above techniques could be too early due to the effects of spectral veiling.

4.3 Conclusions from the Spectroscopic Survey

Our optical spectroscopic survey, although incomplete at the present time, has provided us with valuable information on the characteristics of companions to the Ae/Be stars. From the spectra obtained to date, we conclude that the aggregates associated with Ae/Be stars are comprised primarily of late-type stars.

Table 4.1. Depth-of-Feature Analysis

Feature	**Sidebands**	**Comments**
Mg I 5175	$\lambda\lambda$5050, 5300	"b" triplet line; luminosity indicator in GK stars; temperature sensitive mid-G and earlier; in low-SNR regime of our spectra due to dropoff in grating efficiency
Na I 5892	$\lambda\lambda$5820, 6100	affected by He I 5876 and interstellar Na I in OB stars; weak in early A stars; temperature- and luminosity-sensitive midA-K; luminosity-dependent M0 and later
Mn I ,Fe I 6015	$\lambda\lambda$5820, 6100	appears G0; possibly not useful
Ca I 6162	$\lambda\lambda$6100, 6370	appears A9; temperature sensitive FGK
TiO 6180	$\lambda\lambda$6100, 6370	appears K6-K7; watch for CaH 6386 in sideband; highly temperature sensitive for K5-M stars
Fe II 6456	$\lambda\lambda$6370, 6650	weak after A0 but temperature sensitive through F
Ca I ,Fe I 6497	$\lambda\lambda$6370, 6650	luminosity indicator in KM stars
Hα 6563	$\lambda\lambda$6370, 6650	temperature and luminosity sensitive for all types, although often in emission
TiO 6760	$\lambda\lambda$6650, 7035	central wavelength chosen to avoid nebular emission
TiO 7100	$\lambda\lambda$7035, 7400	highly temperature sensitive for K5-M stars; lower bandpass chosen to avoid atmospheric H_2O absorption and nebular emission
O I 7772	$\lambda\lambda$7500, 8050	blend of 7772, 7774, 7775 lines; appears late B; temperature sensitive BAF; disappears by F8
TiO 7800	$\lambda\lambda$7500, 8050	appears at M3
Na I 8190	$\lambda\lambda$8050, 8400	triplet line; luminosity indicator in M stars; sideband contains CN 7878-8068 later than mid-G
Ca II 8542	$\lambda\lambda$8400, 8800	measures strongest of infrared Ca II triplet; appears after A0; temperature sensitive through F, then constant strength though K3 and luminosity sensitive M0 and later
TiO 8880	$\lambda\lambda$8800, 9190	appears mid-M

Table 4.1.

Furthermore, many of the spectra exhibit at least Hα (as well as Ca II triplet and forbidden lines in a few cases) in emission.