Chapter 3

Optical Spectroscopic Surveys of Photometrically Selected Pre-Main Sequence Star Candidates

The full Quest-2 photometric catalogs contain ~ 2 million and ~ 3 million stars with measurable and calibratable r/i/g photometry in USco and Taurus, respectively, and encompass a total of $\sim 400 \text{ deg}^2$ of sky. All stars in Taurus and $\sim 1/3$ of the stars in USco have been monitored over a period of 6 or 7 nights comprised in total of 12 (Taurus) or 24 (USco) individual observations. Photometric precision between observations ranges from ~ 0.02 mag to >0.1 mag dependent upon the brightness of the star and with which of the 112 CCDs it was observed. These catalogs have the potential to produce a large variety of science, and my thesis work only begins to scratch the surface of the data.

For the purpose of my thesis, I am interested primarily in using the Quest-2 optical photometry to identify young pre-main sequence (PMS) stars. Nearby young stars still undergoing contraction are systematically more luminous than their mainsequence counterparts, and thus occupy a sequence in an optical color-magnitude diagram (CMD) that is correspondingly brighter than the sequence occupied by most of the field stars. However, the position of a star in a color-magnitude diagram is dependent on mass, age, extinction, distance, and the possible presence of a circumstellar disk. Unless these parameters can be measured through independent observations (which in most cases is not yet possible), membership of individual stars cannot be determined. Thus, generally speaking, photometry alone is insufficient for identifying young stars on an individual basis. For a survey such as the one discussed here, which covers a very large spatial extent (hundreds of square degrees) and seeks to identify members of low stellar-density associations, field star contamination will be large and statistical estimates concerning the extent and characterization of the field star population must be derived. Thus, mass, age or spatial distributions derived for these associations from photometry alone represents only statistically probable distributions, which may or may not accurately represent the association.

Follow-up spectroscopic observations of potential PMS stars identified photometrically *can* confirm membership for individual association members and uniquely determine a star's extinction and possible disk excess, thus allowing placement of a star on an HR diagram from which mass and age can be derived. In this chapter I detail my follow-up spectroscopic program, including the criteria used to select candidate PMS stars from the photometric data. The spectroscopic program was carried out using telescopes in both the northern (Palomar Observatory) and southern (Cerro Tololo Intra-American Observatory) hemispheres, and took place during a total of 25 nights of observing. For both the Palomar and the Cerro Tololo data, I discuss the observations, reduction, and analysis, detailing association membership confirmation and spectral type classification methods.

3.1 PMS Star Candidate Selection

The full (junk-free) catalogs contain ~2 million and ~3 million stars in USco and Taurus, respectively, most of which are field stars. To produce a reliable list of candidate PMS stars, I applied several constraints to the source catalogs with the aim of using colors and magnitudes to isolate bona fide PMS stars. The first criterion imposed on the Quest-2 data was to require stars be detected at both the r- and i- bands, thus ensuring optical color information be present for candidate selection. I rejected all objects which had a 'confusion' flag in the catalog indicating that more than one detection was made on a single scan within 0.8" (see §2.2.1). This requirement has the disadvantage of excluding a priori any star with a close binary companion (≤ 110 AU away in projected distance) capable of being resolved in my survey (≥ 20 AU away in projected distance). However, the implications of this constraint are relatively insignificant for the samples of low mass stars and brown dwarfs I will be discussing, as separations for low mass binary systems are predominantly observed to be small (≤ 20 AU; cf. Kraus et al. 2006 and references therein) and would not be resolvable with Quest-2.

I matched the entire dataset to the 2MASS All Sky Catalog (Skrutskie et al., 2006) using a 2" matching radius. Average offsets between Quest-2 and 2MASS coordinates were +0.2" in RA and +0.04" in Dec. I considered stars to be potential PMS candidates only if they had a corresponding 2MASS detection. This criterion biases the final catalogs against faint blue objects to which 2MASS is not sensitive. However, because I am interested only in the reddest 1% of objects in either region (see below for details), and those bright enough to be observed spectroscopically ($r \leq$ 20 mag), this bias does not affect candidate selection in practice. Figure 3.1 shows contour optical color-magnitude diagrams of all Quest-2 sources (black) and those with 2MASS detections (green) in both USco (left) and Taurus (right). As can be seen, the red side of the color-magnitude diagram brighter than $r \sim 20$ is not substantially affected by excluding objects without a 2MASS detection. Figure 3.2 shows the converse data. Black contours represent $K_S, H - K_S$ data for all 2MASS point sources within the USco survey region; green contours represent 2MASS sources with Quest-2 detections. This figure illustrates that the Quest-2 sources are an unbiased representation of the 2MASS data in this region, excepting the bright end for which the Quest-2 photometry saturates.

The final USco and Taurus source catalogs from which PMS candidates were selected contained ~600,000 and ~1.1 million stars, respectively, with $riJHK_S$ magnitudes (and g, when detected) and no neighbors within 0.8". From these datasets, I selected candidate PMS stars based on their colors and magnitudes indicating they could be young, low mass PMS stars. I used three levels of selection criteria. In each of figures 3.3–3.5, objects which meet the selection criteria outlined below are shown



Figure 3.1 Optical color-magnitude diagrams of all Quest-2 sources (black) and those with 2MASS detections (green) in USco (left) and Taurus (right). For both black and green contours, data are represented at 90% to 10%, 5%, 2%, & 1% of the peak level.



Figure 3.2 2MASS color-magnitude diagrams of all 2MASS point sources within the USco survey region (black), and those with Quest-2 detections (green). For both black and green contours, data are represented at 90% to 10%, 5%, & 2% of the peak level. Left and right panels show respectively all 2MASS sources, and only those with 'good' 2MASS photometry (quality flag 'A') in all three JHK_S -bands. Note the differences in both color and magnitude ranges between right and left panels. Note also the faint blue bump in the left-hand panel which corresponds to stars with poor quality 2MASS photometry (see Skrutskie et al. 2006).

as discreet points. Candidates observed spectroscopically at Palomar (§3.2) or Cerro Tololo (§3.3) metting all of the selection criteria outlined below are shown as large magenta and blue points, respectively.

Because Quest-2 was a new instrument at the time these observations were taken, the reduction software has undergone several iterations resulting in the photometric data being re-reduced several times. Therefore, I did not derive the calibrations from Quest-2 instrumental magnitudes to (approximate) Sloan magnitudes until after most of the follow-up spectroscopy had been observed. I was reluctant to choose candidates based on the colors and magnitudes that correspond to particular optical isochronal ages as such isochrones would be specific to a particular filter set. Thus, I felt a selection based on relative optical colors and magnitudes within each survey region would provide the most consistent and unbiased selection. For the spectroscopic observations presented here, I considered as potential candidate PMS stars all sources red-ward of a linear approximation of the 1% data contour in an r, r - i CMD (see figure 3.3).

Near-infrared photometry were also considered during selection of PMS star candidates. In figure 3.4 I show a near-infrared color-color diagram. Solid lines represent the dwarf (bottom line) and giant (top line) loci. The dashed line represents the classical T Tauri star locus as defined by Meyer et al. (1997). Beyond this point I considered only objects which had 'good' 2MASS photometry (quality flag 'A') in all three JHK_S -bands. Any star with $J-H, H-K_S$ colors consistent with those expected for background giants $[(J-H) > 0.6(H-K_S)+0.6$ or $(J-H) > 1.69(H-K_S)+0.29]$ was excluded.

After applying the above selection criteria I identified ~2350 and ~4800 photometrically selected candidate PMS stars in USco and Taurus from a total of ~400 \deg^2 of sky. As discussed at the start of this chapter, due to interstellar extinction and distance effects, optical and near-infrared colors and magnitudes alone are not a unique indicator of youth. Therefore, it is necessary to obtain spectroscopic follow-up observations for all photometrically selected candidates to determine an object's spectral type and confirm the presence of spectral features indicative of youth. Because



Figure 3.3 Optical color-magnitude diagram of all Quest-2 sources in final USco and Taurus catalogs with $riJHK_S$ detections. Contours represent data at 90%–10%, 5%, 2%, and 1% of the peak level. Objects red-ward of a linear approximation of the 1% contour are shown as discrete points. Objects for which I have spectral data taken at Palomar (magenta) or CTIO (blue) are shown as large symbols.



Figure 3.4 2MASS $J - H, H - K_S$ color-color diagram for all data in USco and Taurus represented as contours at 90% to 10%, 5% and 2% of the peak level. Shown as discreet points are all objects that appear red-ward of the 1% data contour in an optical CMD and that do not have colors consistent with those of background giants. Solid lines are dwarf zero-age main sequence (O5–M8) and giant loci (G0–M7). The dashed line represents the classical T Tauri locus as defined by Meyer et al. (1997). Spectroscopic targets presented here are shown as large circles.



Figure 3.5 $r, r - K_S$ color-magnitude diagram for the stars that meet optical and near-infrared selection criteria shown in Figures 3.3 & 3.4 and which appear red in $r - K_S$. Spectroscopic targets presented here are shown as large circles.

it was not possible to observe all the candidates spectroscopically, I chose to focus my efforts on candidates red in $r - K_S$ first, specifically targeting new very low mass stars and brown dwarfs. Thus, I narrowed my candidate list to include only stars satisfying $r < 2.57(r - K_S - 3) + 13$ as shown in figure 3.5. Photometry for seven of the spectral targets (three in USco and four in Taurus) has changed significantly since the spectroscopic observations were taken such that they would no longer be considered candidates. All such objects were determined to be field dwarfs based on their spectra (see chapters 4 and 5).

Although g-band data was not used in the selection criteria, $\sim 50\%$ of the candidates in each region have a g detection. Figure 3.6 shows an (r - i) vs. (g - r)color-color diagram for all data with r, i, g detections and 2MASS detections. Data meeting the selection criteria outlined above with a detection in the g-band are shown as discrete points. Of the candidates we observed spectroscopically, $\sim 70\%$ in Taurus and $\sim 35\%$ in USco have a g-band detection.

3.2 Palomar Spectroscopy

Once candidate PMS stars were selected, I pursued spectroscopic follow-up observations both at Palomar Observatory (USco and Taurus) in the northern hemisphere, and at Cerro Tololo Inter-American Observatory (CTIO; USco only) in the southern hemisphere. In total, the spectroscopic data were taken during five different observing runs comprised of 20 nights at Palomar and 5 nights at CTIO. In this section I present the Palomar data, and in §3.3 I present data taken at CTIO.

Moderate-resolution spectra of 190 candidate PMS candidates in Taurus were taken with the Double Spectrograph on the Palomar 200-inch telescope on the nights of Dec. 9–11 2004 and Nov. 23–27 2005. In USco, I observed 167 objects with the same telescope and instrument during the nights of June 8–12 2005, May 16–19 2006, and June -1-2 2006. All data were taken with the red side of the spectrograph through either the 1.5" or the 2" slit using a 5500 Å dichroic and a 316 lines mm⁻¹ grating blazed at 7500 Å. This set-up produced wavelength coverage from 6300 to



Figure 3.6 Optical r - i, g - r color-color diagram for all data in USco and Taurus with 2MASS detection represented as contours at 90% to 10%, 5% and 2% of the peak level. Shown as discreet points are objects that meet all of the selection criteria outlined in §3.1. Spectroscopic targets presented here are shown as large circles.

8825 Å at a resolution of $R \sim 1250$. Typical exposure times were 300–900 sec, and up to 1800 sec for the faintest targets ($r \sim 21$). Spectrophotometric standard stars (Massey et al., 1988) were observed throughout each night for flux calibration. All sources were processed, extracted and calibrated using standard IRAF tasks.

In addition to my program targets, I also observed a range of spectral main sequence standards (K5-L3), giant standards (K7-M9), previously identified Taurus objects (K3-M7.25; Briceño et al. 2002, Luhman 2004b) and previously identified USco objects (K3-M8; Preibisch & Zinnecker 1999, Ardila et al. 2000, Martín et al. 2004). I observed several members of the Hyades (~650 Myr; Lebreton et al. 2001), Pleiades (~115 Myr; Basri et al. 1996), AB Dor (~75-150 Myr; Luhman et al. 2005), Beta Pic (~11 Myr; Ortega et al. 2004) and TW Hya (~8 Myr; de la Reza et al. 2006) associations. Together, these observations provide a very broad range of standards in both spectral type (temperature) and surface gravity (age).

3.2.1 Temperature Classification

Figure 3.7 shows spectra for dwarf stars of spectral types M3, M6 & M8. The dominant molecular absorption features present are attributed to titanium oxide (TiO). These features increase in strength from mid-K through ~M7 spectral types at which point TiO absorption begins to decrease. Vandium oxide (VO) absorption starts to dominate spectra by early-L types. I have defined or adopted from the literature several band indices to measure the strength of the TiO absorption features. I find two in particular to be diagnostic. TiO-7140 measures the strength of TiO λ 7140 Å absorption compared to a continuum band at λ 7035 Å (Wilking et al., 2005). This index is defined as TiO-7140=F_{λ 7140}/F_{λ 7035} with bandwidths of 50 Å. TiO-8465 is a new index I created (TiO-8465=F_{λ 8465}/F_{λ 8415} with bandwidths of 20 Å) to measure the strength of TiO λ 8465 Å absorption compared to a continuum band at λ 8415 Å. In Figure 3.7, light and dark shaded regions respectively show location of the TiO and continuum bands used in my analysis.

The left side of figure 3.8 shows a plot of TiO-8465 vs. TiO-7140 for observed



Figure 3.7 Spectra for M3, M6, and M8 type dwarf stars. Dominant TiO and VO features are labeled. Light and dark shaded regions respectively show location of the TiO and continuum bands used in spectral classification.



Figure 3.8 Temperature-sensitive TiO-7140 vs. TiO-8465 indices. Blue X's represent measured indices for field dwarfs and members of the Hyades (~650 Myr), Pleiades (~115 Myr) and AB Dor (~75–150 Myr) associations. Green X's show measured indices for intermediate-age spectral standards from Beta Pic (~11 Myr), TW Hya (~8 Myr), and Upper Sco (~5 Myr). Red X's show measured indices for young Taurus members (~1–2 Myr). In the right panel, black symbols are measured indices for Quest-2 PMS candidates. The effects of extinction and veiling are shown as vectors (see §3.2.3). This diagram is useful for classifying stars with spectral types M3-L3.

spectral standards. Blue X's are measured indices for dwarf stars and members of the Hyades, Pleiades, and AB Dor (ages > 75 Myr). Green X's are measured indices for members of TW Hya, Beta Pic and known members of Upper Sco (ages 5–10 Myr), and red X's are measured indices for known Taurus members (ages $\sim 1-2$ Myr). This diagram is useful for classifying stars with spectral types M3–L3. No significant age dependence exists between measured TiO indices of older stars (blue) and young (red) or intermediate-age (green) PMS standard stars. In the right side of figure 3.8, black circles represent measured indices for program sources in Taurus and USco. The measurements predominantly follow the locus determined by the spectral standards. Specific outliers are discussed in detail in chapters 4 & 5.

Spectral types were determined first from quantitative analysis using an object's

measured TiO indices. More weight was given to the value of the TiO-8465 index which I find particularly insensitive to the effects of reddening and veiling (§3.2.3). However, using the TiO indices alone I can not uniquely recover spectral types for the dwarf and PMS standard stars. This ambiguity is due in part to uncertainties in published spectral types and in part to systematic differences between spectral classification schemes of different authors. Therefore, it was necessary to examine each spectrum by eye and use the information from the entire spectral range in final type determination. All program spectra were thus compared visually to a large grid of standard spectra. Typical revisions to the quantitative spectral types were at the level of ≤ 1 subclass.

3.2.2 Surface Gravity Classification

In addition to determining spectral types, it was also necessary to determine which of the candidates are bona fide PMS stars. Because low mass young stars are still undergoing contraction to the main sequence, they have systematically lower surface gravity than their older main sequence star counterparts. I therefore use surface gravity to roughly define stellar age. Several diagnostics of surface gravity exist in this wavelength regime which can be assessed in low and moderate resolution spectra. The three most prominent features are due to Na I (λ 8183 & λ 8195 Å) and K I (λ 7665 & λ 7699 Å) doublets, and CaH molecular absorption at $\lambda\lambda$ 6975 Å. Figure 3.9 shows a sequence of three M6 standard stars: a high-gravity main-sequence star (GJ406), a 5 Myr intermediate-gravity USco object (DENIS-P16007.5-181056.4) and a 1 Myr low-gravity Taurus object (MH05). Gravity sensitive absorption features are labeled and increase in strength with increasing stellar age and gravity. The location of Li and H α lines are also shown.

To assess surface gravity quantitatively, I have developed a gravity-sensitive index to measure the strength of the Na I doublet, defined as Na-8190= $F_{\lambda 8189}/F_{\lambda 8150}$ with bandwidths of 30 Å. Figure 3.10 shows a plot of the gravity-sensitive Na-8190 index as a function of the temperature-sensitive TiO-8465 index for all stars earlier than



Figure 3.9 Sequence of three M6 stars: a high-gravity main-sequence star (GJ406), a 5 Myr intermediate-gravity USco object (DENIS-P16007.5-181056.4) and a 1 Myr Taurus object (MH05). Gravity- sensitive absorption features are labeled and increase with increasing stellar age and gravity. Light and dark shaded regions respectively show location of the Na I and continuum bands used in surface gravity analysis.



Figure 3.10 TiO-8465 index vs. the gravity sensitive Na-8190 index. Symbols are as in figure 3.8 with the addition of cyan X's which represent measured indices for giant standard stars. Objects with higher surface gravity have more Na I absorption present in their spectra and thus, a smaller Na-8190 index. In the right panel, black symbols are measured indices for Quest-2 PMS candidates. As in figure 3.8, the effects of veiling and extinction are shown as vectors (see §3.2.3).

M9. On the left is shown measured indices for spectral standards. Colors are as in figure 3.8 with the addition of cyan X's for giant stars.

I find the Na-8190 index to be a robust diagnostic that clearly separates low, intermediate and high gravity stars for spectral types later than M2 and earlier than M9. Objects with spectral types outside of this range do not exhibit substantial Na I absorption. Measured Na-8190 indices for ~ 100 Myr Pleiades stars are indistinguishable from those for dwarfs at similar spectral types (see chapter 4 for more details). In figure 3.10, black symbols in the right-hand panel show measured indices for program PMS star candidates in USco and Taurus. A large fraction of the candidate PMS objects in both regions have measured Na-8190 indices consistent with their having surface gravity less than that of field dwarfs at similar spectral types. Gravity signatures in all candidate PMS star spectra were additionally verified visually. Discussion on results for the individual associations is reserved for chapters 4 & 5.

3.2.3 Extinction and Veiling

While most of the known low mass Taurus members have low extinction ($A_V \sim 1$; e.g., Kenyon et al. (1994)), and hot OB stars have dispersed much of the dense gas and dust within the USco association, the quantitative indices used in classification can be affected by interstellar reddening and this fact must be taken into account during classification. I first derived an approximate, qualitative A_V measurement for each star by visually dereddening its spectrum until its slope matched that of a standard star of the same spectral type. I find that almost all of the PMS stars newly identified from their surface gravity signatures have $A_V < 1$ based on spectral slope from $\lambda 6300$ to 8825 Å. For the stars in the USco survey, more precise extinction values are derived from each object's spectral type and colors in chapter 5, and in all cases I find agreement to within one magnitude of my visual estimate.

To assess the effect reddening has on my quantitative classification indices I artificially reddened all standard stars by $A_V=10$ mag, the maximum extinction inferred from large-beam dust measurements towards my survey region in USco excluding the young ρ Ophiuchus molecular cloud core (Schlegel et al., 1998). I measured index strengths for artificially reddened spectra and find average index shifts of -0.1 for TiO-7140 and -0.04 for TiO-8465. As can be seen from Figure 3.8, index shifts at this level are not sufficient to affect my quantitative temperature determination from TiO indices at the 0.5 subclass level. Ten magnitudes of extinction could affect the Na-8190 index by an average shift of -0.05. However at a level of reddening more consistent with actual measured values for new USco members ($A_V \leq 2$; table 5.1), I find a much more moderate shift of -0.01 which would not be sufficient to make a dwarf star look like a PMS star for objects between M2 and M9. In Taurus, the maximum extinction within my survey region as inferred from large-beam dust maps (Schlegel et al. 1998) is $A_V=6$ mag. Results of reddening the standards by this amount are shown for a typical M5 star on figures 3.8 & 3.10. Reddening at this level, in addition to not shifting the spectral indices by a significant amount to affect classification, can be easily identified upon visual assessment of a spectrum's overall slope.

I must also consider the effects of veiling at optical/UV wavelengths which may occur in the presence of either excess hot emission from an accretion shock or excess thermal emission from dust grains in a circumstellar disk. In both cases the excess emission veils (decreases) the strength of the molecular absorption features used in classification and will cause a star to be systematically classified too hot (early) in spectral type. The veiling index is defined as $r_{\lambda} = F_{\lambda,ex}/F_{\lambda,ph}$, where "ex" indicates excess and "ph" indicates photosphere. I tested several scenarios to determine the existence and magnitude of any bias in the spectral types attributable to veiling. The maximum shift produced from these experiments is shown in figures 3.8 and 3.10.

First, I added to all spectra a $T_{eff}=1400$ K blackbody consistent with a cool disk around a low mass star or brown dwarf at a veiling level of $r_{K}=0.6$, corresponding to the median near-infrared veiling value for K7-M0 classical T Tauri stars (Meyer et al., 1997). Theoretically, the Wein tail of such a blackbody could affect my spectral indices around $0.8\mu m$. I remeasured indices for veiled standard spectra and found, as expected, excess thermal emission from a cool disk has very little effect on optical spectra. Next, I investigated the effects of veiling from a hot accretion shock. I used a value of $r_{6500}=0.6$, equivalent to the average optical veiling value for late K and early M stars (White & Hillenbrand, 2004). I added a $\mathrm{T}_{eff}{=}8000$ K blackbody at this level to all standard spectra and rederived the spectral classification indices. I additionally experimented by adding a continuum excess of constant flux at the $r_{\lambda}=0.6$ level, shown by White & Hillenbrand (2004) to be more consistent with observations than a hot blackbody. In both cases, the strength of the TiO-7140 index decreases substantially while the change in the TiO-8465 and Na-8190 indices are much smaller. For this reason, I rely primarily on the TiO-8465 index for temperature classification and believe my surface gravity assessment from the Na-8190 index to be robust to effects of veiling.

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3.3 Cerro Tololo Spectroscopy

Additional spectra of PMS star candidates in USco were taken at Cerro Tololo Inter-American Observatory (CTIO) using the Hydra multifiber spectrograph on the Blanco 4-m telescope during the nights of 2005 July 24–28. In total, 26 fields were observed with the Site2k×4k CCD through the KPGLF grating. The setup provided wavelength coverage from \sim 6300 to 8660 Å at a resolution of 1.15 Å/pixel.

My strategy for prioritizing stars was first to place as many fibers as possible on stars meeting the criteria outlined in §3.1, thus providing a sample of candidates analogous to those observed at Palomar. Remaining fibers were placed on stars meeting one or more of the criteria outlined in §3.1, but not all three. For the practical requirements of the Hydra observations, stars were assigned to either 'bright' fields (corresponding to $r \leq 16.5$) or 'faint' fields (corresponding to $16.5 \leq r \leq 18.5$). Exposure times ranged from 900 to 1800 sec for bright fields (dependent on weather conditions) and were set at 2700 sec for faint fields. In total, 10 bright and 16 faint fields were observed during the 5 nights. At each fiber configuration I observed a comparison lamp spectra and a quartz lamp spectra to allow determination of the dispersion solution and throughput correction during data reduction. Biases and dome flats were taken each afternoon with all working fibers put in the 'large circle' configuration. Milk flats (see below) were taken once during the observing run.

3.3.1 Image Processing

All frames were first pre-processed (bias correction and trimming) using CCDPROC. Milk flats were obtained on the second afternoon of observing. This type of observation is an exposure of the daytime sky and is taken through a plate of milky glass placed between the output of the fibers and the spectrograph camera. The purpose of such an observation is to allow removal of pixel-to-pixel variations from the data without having to worry about fiber placement. A spectral response image was created by smoothing in both X and Y directions. The original milk flat was then divided by the spectral response image to create an image with a value of 1.0 everywhere except where pixel-to-pixel variations exist. All data and calibration frames were divided by the this image.

Subsequent data reduction was done using the IRAF dohydra task. All data for a given night were divided by the dome flat taken that afternoon. Individual fiberto-fiber throughput corrections (which change for each configuration) were made by dividing each object frame by the corresponding quartz lamp spectra taken in the same fiber configuration. Wavelength calibration was done by matching each object spectrum to the lamp spectrum taken with the same fiber during the lamp exposure taken for that specific configuration.

3.3.2 Sky Subtraction

For each field, a single sky spectrum was made using the sky generating tasks within dohydra. Typically, $\sim 5-20$ fibers were placed on sky during each observation. The task first allows rejection of any anomalous sky spectra which may have inadvertently fallen on a star or a clump of nebulosity. Remaining sky spectra were averaged together using a 3-sigma clipping algorithm. The hydra field of view is large, 40' on a side. While much of the nebular material has been dispersed by hot stars in USco, in places a significant amount remains such that the sky level was not constant across the entire field. Thus, I found subtraction of a single sky spectrum for all spectra within a field often produced insufficient sky subtraction in that for a given spectrum, all sky lines would be systematically over- or under-subtracted. To correct this problem, for each object spectrum and for the sky spectrum I computed the flux in a single sky line chosen to be towards the center of the spectrum at ~ 7316 Å and to be sufficiently isolated that is was not blended with any other sky or stellar lines. I then scaled each object spectrum such that the flux computed for its central sky line matched that of the sky spectrum and then subtracted the sky spectrum. I found, in general, this procedure produced satisfactory results.

3.3.3 Classification

Spectral observations taken through fibers produce flux that varies as a function of wavelength dependent on the fiber configuration, i.e., how the relevant fiber is bent and stretched to place it into position on the star. Thus flux correction of fiber data is inherently very difficult to do because it is not practical to observe a calibrator star through every fiber at every configuration. Thus, I was not able to flux-correct the hydra spectra in an analogous manner to the Palomar data and therefore could not use the quantitative spectral indices (which rely on flux-corrected spectra) to aid in classification. During observations, my primary targets set around UT 6:00 and I used the remaining hours to observe individual standard stars. I took a range of known dwarf stars and giant stars (spectral types K0–M8). In addition, I observed known intermediate-age PMS members of the ~ 30 Myr-old Tucanae Hor association (Mamajek et al., 2004) with early M spectral types. Spectra of previously identified K0–M8-type USco members were observed in the primary fields along with program candidates. Though the overall spectral shape is not meaningful because the spectra are not flux corrected, the depth of absorption and emission features is not substantially affected. All spectra of candidate PMS stars were thus classified by hand through comparison to each other and to standard stars observed with hydra.

In total, the hydra observations yielded ~1150 spectra (of varying quality). I first classified all of the spectra into broad categories. Approximately 450 were determined to be mid K- to M-type stars based on the presence of TiO molecular absorption in their spectra, and a lack of H α absorption (though H α can be seen in emission). The largest constituent of the spectral sample (~650 stars) were intermediate-type stars with spectral types late F through early K. These stars are characterized by a lack of TiO molecular absorption but the presence of Ca II triplet (λ 8498, λ 8542, λ 8662 Å) and H α atomic absorption. Absorption from and the Ba II, Fe I, Ca I blend at λ 6497 Å begins to appear at late F/early G types and increases in strength compared to H α absorption through K spectral types. The remaining stars were determined to have spectral types A-F with deep H α and Ca II triplet absorption but noticeably lacking any absorption at the $\lambda 6497$ Å blend. I saw no evidence of He absorption in any of the spectra and thus concluded that my survey did not probe B- or O-type stars. Thus far, I have derived detailed (at the ~0.5 subclass level) classifications from these data only for those stars whose colors and magnitudes meet all of the selection criteria outlined in §3.1. I discuss these results in chapter 5 along with results from the Palomar spectral observations. The remaining stars are predominantly earlier than spectral type~M2, and are discussed in more detail in chapter 8.

3.4 Summary of Candidate Selection and Spectroscopic Observations

In this chapter I combine the Quest-2 optical photometry with 2MASS near-infrared magnitudes and select candidate PMS stars and brown dwarfs based on their systematic high luminosities above the main sequence and red infrared colors. I present follow-up optical spectral observations taken at either Palomar or CTIO for several hundred candidates in Taurus and USco, and detail temperature and surface gravity classifications of stars based on spectral features. In the next two chapters I discuss implications of survey results in specific regions.