Appendix C

Ongoing Analysis in the Orion Nebula Cluster

Despite extensive discussion of the Orion Nebula Cluster (ONC) in the literature, to date there has been no comprehensive, flux-limited study of its stellar population. The Jones & Walker (1988) proper motion survey showed that about 90% of the stars within 15 arcmin of the Trapezium are cluster members, and at least 50% are photometric variables. The nature of the variable star properties are being investigated by Herbst *et al.* in a long-term monitoring program. We have initiated an optical / infrared imaging and spectroscopic survey of the region within a few pc of the Trapezium stars, with particular attention to objects designated as proper motion members by Jones & Walker (1988) or appearing in the deep optical photometric survey covering the inner 0.3pc of the ONC by Prosser *et al.* (1994). We describe below the data used to construct the preliminary HR diagram presented in Chapter 8 in the main text.

C.1 New Photometric and Spectroscopic Observations

V and I_C CCD data were obtained for the ONC on the same optical imaging run as is described in the main text. The photometric reductions were similar to those for our other CCD data, although the heavy and variable nebulosity in this region required special attention in selecting aperture and sky annuli.

Classification-resolution spectra covering approximately $5000 - 9000\,\AA$ at $1.97\,\AA$ pixel^{-1} (~ 6 Å per resolution element; $R \approx 1250$) were obtained for 179 stars on two nights in 1994 January with the KPNO HYDRA multi-object fiber-fed bench spectrograph and 4m telescope, through variable cirrus. An unfortunate

choice of order-sorting filter (GG-420) led to contamination in our spectra longward of 8400 $\AA$ from second-order blue photons. In most cases this error was not an issue, as amongst our program objects there is typically very little light emitted in the blue. For intrinsically blue stars and for bright stars (I $\lesssim$ 10 mag) of all spectral types, however, blue photons were apparent in the form of excess continuum and, in some cases, even Balmer lines at the red end of our spectra.

On 1994, 2 January, 90 program objects were observed through increasing cirrus in 2 exposures of 1200 seconds and 1 exposure of 600 seconds. A single fiber was assigned to a sky position during these "on-field" integrations. A 600 second "off-field" exposure was taken after offsetting the telescope 4" west on the sky. This procedure was used in order to establish a near-by off-field position for every fiber over the significantly variable (in space) nebula. These data were obtained over an airmass range of 1.29-1.32. On 1994, 3 January, 89 program objects were similarly observed in 2 "on-field" and 1 "off-field" exposures of 1200 seconds each. For these observations the airmass range was 1.72-1.97 and the seeing 1.5-2".

The two-dimensional images were processed first by subtracting the bias voltage from the original CCD frames. The "on-field" exposures were combined, using the IRAF routine IMCOMBINE, to the average value for each pixel after scaling by the exposure times and employing sigma-based pixel rejection. The combined images were corrected for scattered light using the IRAF task APSCATTER. The IRAF routine 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. "On-field" and "off-field" exposures were extracted separately. The final step was to effect sky subtraction using the IRAF task SCOMBINE. This technique provides residual spectra of excellent quality

given the complexity of the region, except in extremely strong and spatially variable nebular lines, most notably Hα 6563 Å .

C.2 The Sample

In a crowded and dynamically complex star-forming region such as the Orion Nebula Cluster, how can we be sure that our spectroscopic sample is representative of the young stars in the region? For these observations, fibers were assigned to stars in a manner such that the maximum number (from 95 possible) of available fibers able to be placed on program objects, with priority given to stars in the Prosser *et al.* (1994) survey (I and those remaining assigned to Jones & Walker (1988) proper motion members. Stars from the Prosser *et al.* survey for which we were able to obtain spectra range in brightness from I=13-17.5 mag. The quoted limits of the Jones & Walker survey are I$\sim$ 13 in the region of bright nebulosity and I$\sim$ 16 in the outer parts of the nebula. The spectroscopic sample is therefore considered to be unbiased since it is random with respect to stellar brightness and all stars are assumed to lie at the same distance.

Despite the apparent lack of systematic effects in our spectroscopic sample, we have found the following: nearly *all* ($> 95\%$) of the spectra obtained in the HYDRA observations described above, are those of stars with spectral types K2 and later.

C.3 A Preliminary HR Diagram

An HR diagram for the HYDRA spectroscopic sample was constructed using our derived spectral types along with the temperature scale of Cohen & Kuhi (1979), and the V,I_C photometry of Prosser *et al.* 1994, Herbst *et al.* (private communication), and our own from the CCD frames. We note that at the present time, photometry is available for only 129 / 179 of the stars for which we have

determined spectral types! Stellar luminosities were calculated as described in the main text, except that for this set of stars we have used V-I_C (instead of $R_C - I_C$) colors to determine the individual extinction values. The distance assumed to the Trapezium region is 470 pc; the uncertainty in luminosity introduced by assuming either an error in the distance of $\pm$20pc, or a comparable intrinsic stellar dispersion in distance, 0.075 dex. Other sources of luminosity error are described in the main text.

Additional stars not in the Jones & Walker or Prosser *et al.* surveys, but claimed to be proper motion members by McNamara *et al.* (1989), are also included in the HR diagram shown in Figure 8.7. These stars spread over central, southern, and northwestern fields in relation to the Trapezium, with a maximum (projected) radial distance of 10 pc; more than one-half of the McNamara stars are within the inner 2 pc, however. These additional stars were placed in the HR diagram based upon blue spectra of stars brighter than B=14mag, also obtained with the HYDRA multi-object spectrograph at KPNO but at echelle resolution in 1992, November and in 1993, January, and the dereddened B-V colors of either McNamara *et al.* (1989) or Walker (1969). We note that the spectral types derived for the FG stars in the echelle sample are better than those which would have been obtained with red classification-resolution HYDRA spectra similar to those obtained in 1994, January, due to the difficulty of classifying stars in this temperature range in the red spectral regime.

Having established an HR diagram covering the extended area encompassing the ONC, we are now in a position to search for either age or mass trends as a function of radius. To do so, we examine the HR diagram as a function of projected radius from $\theta^1 C$ Ori. In the current discussion, we consider only stars in the inner 2 pc. At (projected) radii $r < 0.5$pc, for stellar masses $M < 2$ $M_\odot$ the Kelvin-Helmhotz ages are strictly less than 2 Myr ($\sim 90\%$ are less than 1 Myr)

while for $M > 2$ $M_\odot$ there are several stars with Kelvin-Helmholtz ages greater than 5 Myr. At (projected) radii $0.5 < r/pc < 1.0$, the same trend is found: for stellar masses $M < 2$ $M_\odot$ the Kelvin-Helmhotz ages are less than approximately 3 Myr while for $M > 2$ $M_\odot$ all stars have Kelvin-Helmholtz ages greater than 5 Myr. Thus within the ranges of projected radii considered here, stars located further from the center (defined to be the location of $\theta^1 C$ Ori) appear to be older than those closest to the center. As discussed in the main text, there is some uneasiness about the literal interpretation of pre-main sequence mass tracks and isochrones. However, the results of that discussion should not affect the apparent makeup of the stellar population as a function of radial distance. For completeness, we reiterate our presentation in the main text, by stating that when all stars at projected radii $r < 2$ pc are included, we find that the 1) the low-mass stars populate a region extending in luminosity from near or slightly above the "birthline" to the 2 or 3 Myr isochrone; 2) the high-mass stars are on or near the zero-age main sequence with inferred ages comparable to those derived for the low-mass stars; and 3) the intermediate-mass stars appear to be older than the lower-mass stars.

Can we say anything from this preliminary HR diagram about the mass distribution in the Trapezium region? Although our survey is far from being "complete" at the low mass end, we do include in this HR diagram all of the intermediate- and high-mass stars (unless they are heavily extincted) found at radii $r < 0.5$ pc from θ^1 C Ori. Looking at the mass distribution as we do in the main text, we find a ratio of intermediate- to low-mass stars, $N(1 < M/M_\odot < 10)$: $N(0.1 < M/M_\odot < 1)$ of 0.34 or less, which is not exceptionally unsual although it is higher than the nominal value of 0.16. Additional spectroscopic data is needed in order to address the mass function issue properly and confirm or deny our impression that the distribution of stellar masses in the ONC is close to that

expected from standard mass functions. What *is* unusual about the Trapezium region is that there are 6 stars with masses $M > 10$ $M_{\odot}$ located within this small area, translating into a mean (true) separation between the massive stars of only about 0.44pc.