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THE INITIAL MASS FUNCTION AND DISK FREQUENCY OF THE $\rho$ OPHIUCHI CLOUD: AN EXTINCTION-LIMITED SAMPLE

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ABSTRACT

We have completed an optical spectroscopic survey of an unbiased, extinction-limited sample of candidate young stars covering 1.3 deg$^2$ of the $\rho$ Ophiuchi star-forming region. While infrared, X-ray, and optical surveys of the cloud have identified many young stellar objects (YSOs), these surveys are biased toward particular stages of stellar evolution and are not optimal for studies of the disk frequency and initial mass function. We have obtained over 300 optical spectra to help identify 135 association members based on the presence of H$\alpha$ in emission, lithium absorption, X-ray emission, a mid-infrared excess, a common proper motion, reflection nebulosity, and/or extinction considerations. Spectral types along with R- and I-band photometry were used to derive effective temperatures and bolometric luminosities for association members to compare with theoretical tracks and isochrones for pre-main-sequence stars. An average age of 3.1 Myr is derived for this population which is intermediate between that of objects embedded in the cloud core of $\rho$ Ophiuchi and low-mass stars in the Upper Scorpius subgroup. Consistent with this age we find a circumstellar disk frequency of 27% ± 5%. We also constructed an initial mass function for an extinction-limited sample of 123 YSOs ($A_v < 8$ mag), which is consistent with the field star initial mass function for YSOs with masses $>0.2 M_\odot$. There may be a deficit of brown dwarfs but this result relies on completeness corrections and requires confirmation.

Key words: ISM: individual objects ($\rho$ Ophiuchi cloud) – open clusters and associations: individual (Upper Scorpius) – stars: formation – stars: pre-main sequence

Online-only material: color figure

1. INTRODUCTION

An important question in the theory of star formation is whether the initial mass function (IMF) of stars is universal. Variations in the IMF from region to region may hold clues to the roles of accretion, fragmentation, and ejection in producing the stellar mass spectrum (e.g., Bonnell et al. 2007). One of the best places to investigate the IMF is in molecular clouds with active star formation since cluster membership is well-determined, low-mass stars have had a limited amount of time to segregate, and one can associate variations in the IMF to the physical conditions of the cloud. Due to large columns of dust obscuring all but the brightest objects in the cloud, IMF studies of young clusters require unbiased, extinction-limited spectroscopic surveys (e.g., Bastian et al. 2010).

The $\rho$ Ophiuchi molecular cloud complex is a well-studied, nearby region of active star formation (see Wilking et al. 2008 for review). Located at 130 pc from the Sun (Mamajek 2008), its proximity guarantees access to the broadest range of luminosity and mass. Most recently, the Spitzer Space Telescope surveyed $\rho$ Ophiuchi in the mid- and far-infrared as part of the Legacy and guaranteed time programs. About 292 young stellar objects (YSOs) were identified with infrared excesses due to circumstellar disks (Evans et al. 2009) over a field of view of 6.8 deg$^2$. X-ray studies have also been conducted of the region with ROSAT, XMM-Newton, ASCA, and Chandra revealing more evolved YSOs with magnetic surface activity (Grosso et al. 2000; Gagné et al. 2004; Ozawa et al. 2005). But for studies of the IMF one must sample all phases of pre-main-sequence (PMS) evolution from heavily embedded YSOs in their main accretion phase, to classical T Tauri stars (CTTS), to weak-emission T Tauri stars (WTTS) with little or no circumstellar dust. Optical spectroscopic surveys targeting CTTS and WTTS have been conducted of this region, however these studies have been biased toward objects with X-ray emission or YSOs with suspected H$\alpha$ emission (Bouvier & Appenzeller 1992; Martín et al. 1998; Wilking et al. 2005). Wilking et al. (2005, hereafter Paper I) obtained 136 spectra from 5820 Å to 8700 Å at a resolution of 2.9 Å and identified 88 cluster members in the main L 1688 cloud of the Ophiuchus complex. The members had a median age of 2.1 Myr and included 39 CTTS. However, their survey had a selection bias toward YSOs with H$\alpha$ emission.

In this paper, we present the results of a new optical spectroscopic survey which, when combined with data from Paper I, enables us to construct an unbiased, extinction-limited sample of YSOs in the L 1688 cloud. Section 2 describes this new spectroscopic survey which covered the wavelength range 6249–7657 Å with a resolution of 1.4 Å that enabled us to resolve Li in absorption, an indicator of youth. The analysis of the spectra to derive spectral types and exclude background giants is described briefly in Section 3. Section 4 discusses the results of our analysis including the identification of association members, their spatial distribution, their placement in a Hertzsprung–Russell (H-R) diagram relative to several
2. OBSERVATIONS AND DATA REDUCTION

Over 200 moderate resolution spectra were obtained for 184 stars identified through \( R \)- and \( I \)-band photometry as candidate YSOs. Fifty-two of these stars had spectral classifications. Newly observed YSO candidates numbered 133. These observations are described in detail in the following sections.

2.1. Sample Selection

Candidate YSOs were selected from an \( I \) versus \( (R-I) \) color–magnitude diagram. \( R \)- and \( I \)-band photometry were obtained from short (5 minute) exposure images obtained with the 0.6 m Curtis-Schmidt Telescope located at Cerro Tololo Inter-American Observatory in 1995 March (see also Wilking et al. 1997 for description). The CCD images covered a 67' × 68.5' area centered on R.A.(2000) = 16°27'14.7'', decl.(2000) = −24°30'06'' with a scale of 2''/3 pixel\(^{-1}\). The survey area is shown in Figure 1 relative to the distribution of molecular gas. Photometry was performed using an 8''1 diameter aperture optimized for the 4'' full width at half-maximum of the point-spread function (Howell 1989) with local sky background measured in an annulus 10''–20'' in diameter. Zero points were computed in the Kron–Cousins photometric system using standard star fields established by Landolt (1992). Completeness limits were estimated by adding artificial stars in half magnitude intervals to the images and extracting them using DAOFIND in the Image Reduction and Analysis Facility (IRAF).\(^5\) Recovery of \( \geq 90\% \) of the artificial stars occurred for \( R \leq 18.1 \) mag and \( I \leq 17.0 \) mag. Photometry was not reliable for stars with \( R \leq 12.4 \) mag and \( I \leq 11.8 \) due to saturation of the CCD.

An \( I \) versus \( (R-I) \) diagram for over 2500 stars is presented in Figure 2. The ordinate is the absolute \( I \) magnitude assuming a distance of 130 pc with no correction for reddening. Objects observed spectroscopically are shown by open circles (association members), diamonds (field stars), or "×"s (giants). Isochrones and the ZAMS from the DM models are shown for comparison.

\(^{5}\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
From this diagram, we have drawn a sample for spectroscopic follow-up of stars which are on or above the 10^7 yr isochrone and brighter than our completeness limits. Samples selected from this region of the color–magnitude diagram should be representative for stars earlier than M6 with $A_v \lesssim 3$ mag and ages $\lesssim 10^7$ yr.

Accurate positions ($\sim 0^\prime.5$) for these stars were obtained using the ASTROM program distributed by the Starlink Project and a set of secondary astrometric standards. The secondary position references were 27 Hz emission-line stars with accurate positions determined relative to SAO stars in a 5 deg² region on the Red Palomar Sky Survey plate (Wilking et al. 1987). These positions were compared to counterparts from the Two Micron All Sky Survey (2MASS); matches were found within a radius of 2". Positions were then shifted by +0.2 s in right ascension to bring them into agreement with the 2MASS coordinate system (Cutri et al. 2003).

2.2. Hydra Observations

Optical spectra were obtained for stars located over a 1.3 deg² area centered on L 1688 using Hydra, the multi-fiber spectrograph, on two different telescopes. Fiber configurations were designed to observe the maximum number of candidate YSOs; crowding at the edges of our field restricted the number of sources that could be observed. The first set of observations were made using Hydra on the Blanco 4 m telescope at Cerro Tololo Inter-American Observatory on 2003 August 10–12. The Bench Schmidt camera with the SiTe 2k × 4k CCD gave a 40' field of view. The fibers (2" diameter) coupled with the 790 lines mm⁻¹ KPGLD grating yielded a wavelength coverage of 6275–7975 Å centered near 7125 Å. The spectral dispersion was 0.90 Å pixel⁻¹ giving an effective resolution of 2.7 Å. The resolution at the central wavelength was $\lambda/\Delta\lambda = 2600$. The second set of observations utilized Hydra on the WIYN 3.5 m telescope on 2006 June 15–17. The Bench Spectrograph Camera was used with the T2KA CCD which gave a 1° field of view. The red fiber cable (2" diameter) and the 1200 lines mm⁻¹ grating with a blaze angle of 28°7 were combined with the GG-495 filter to cover the range of 6250–7657 Å centered near 6960 Å. The spectral dispersion was 0.68 Å pixel⁻¹ giving an effective resolution of 1.4 Å. The resolution at the central wavelength was $\lambda/\Delta\lambda = 5000$. Three fiber configurations were observed at each telescope, set to observe overlapping regions of the 1.3 deg² target field.

The spectra were reduced using IRAF. Images were processed for bias and dark corrections using CCDPROC. Multiple exposures of a given field were median-combined and then reduced with IRAF’s DOHYDRA package. The images were flat-fielded using dome flats obtained for each fiber configuration. Sky subtraction was accomplished using the median of 7–10 sky spectra distributed across the field for each configuration. The spectra were wavelength calibrated using 5 s exposures of the PENRAY (CTIO: He, Ne, Ar, Xe) or CuAr (WIYN) lamps taken in each fiber configuration. Scattered light corrections were not made and no flux calibration was performed. In Table 1, we summarize the observations by presenting for each field the observation date and telescope, pointing center, number of candidate YSOs observed, number of exposures, and the total integration time. The typical signal-to-noise ratio for stars with $R = 16$ mag was 30 for the CTIO spectra and 20 for the WIYN spectra as measured by line free regions of the continuum.

| Field No. (YYMMDD) | Telescope | Position (J2000.0) | Sources | No. of Exp. | Int. Time (minutes) |
|-------------------|-----------|------------------|---------|-------------|-------------------|
| 1 030810          | Blanco    | 16:27:05.4–24:45:09 | 24      | 5           | 135               |
| 2 030811          | Blanco    | 16:28:15.2–24:14:04 | 47      | 5           | 135               |
| 3 030812          | Blanco    | 16:26:01.9–24:14:23 | 48      | 5           | 135               |
| 4 060615          | WIYN      | 16:25:47.2–24:41:00 | 32      | 10          | 240               |
| 5 060616          | WIYN      | 16:28:21.6–24:28:00 | 42      | 10          | 240               |
| 6 060617          | WIYN      | 16:27:22.9–24:09:00 | 30      | 10          | 240               |

3. ANALYSIS OF THE SPECTRA

As in Paper I, spectral types were derived from visual classification (visual pattern matching of our smoothed program star spectra with standard star spectra) supported by quantitative analysis of some spectral indices. For the purposes of matching spectral features with those of standard stars, our Hydra spectra were smoothed using a Gaussian filter to the resolution of the standard stars used for direct comparison. All spectra have been normalized to 1 by dividing out a fit to the continuum, carefully excluding regions with emission lines or broad absorption due to TiO. Normalized spectra were smoothed to a resolution of 5.7 Å for comparison with the spectral standards of Allen & Strom (1995). For giants and later type dwarfs (MSV—M9V), optical spectra from the study of Kirkpatrick et al. (1991) were used with an effective resolution of either 8 or 18 Å. The relative strength of absorption due to Hα and a blend of Ba ii, Fe i, and Ca i centered at 6497 Å is the most sensitive indicator of spectral type for F–K stars and the depth of the TiO bands for K–M stars. A rough estimate of the surface gravity of an object is important in distinguishing PMS stars from background giants. The primary gravity-sensitive absorption feature available for analysis in our spectra was the CaH band centered at 6975 Å. This band is evident in the spectra of dwarf stars with spectral types later than K5. Following Allen (1996), we have calculated a CaH index as the ratio of the continuum at 7035 ± 15 Å to the flux in the CaH absorption band at 6975 ± 15 Å and a TiO index (primarily temperature sensitive for stars $\geq$ K5) as the ratio of the continuum at 7030 ± 15 Å to the flux in the TiO absorption band at 7140 ± 15 Å from the unsmeared, normalized spectrum of each program object. In Figure 3, we plot the CaH index versus TiO index for 136 program objects. Error bars are computed based on the 1σ error in the mean in flux averages and propagated to the ratios. The solid lines represent first- or second-order fits to the standard star spectra.
4. RESULTS

Spectral types were determined for 174 of 184 stars in this study. These data are presented in Table 2 along with any previous source names, X-ray associations, R.A. and decl. in J2000, the (R−I) color indices, I magnitudes, and previous spectral classifications. The presence of lithium absorption at 6707 Å and the equivalent width of Hα are also given (emission shown as a negative value). Based on the CaH index, we have identified nine background giants and seven possible dwarfs. Spectral classifications agree well with optical and infrared spectral types previously published by Bouvier & Appenzeller (1992), Martin et al. (1998), Luhan & Rieke (1999), Cieza et al. (2010), as well as those in Paper I. A notable exception is WLY 2-48/ISO-Oph 159. Geers et al. (2007) report an optical spectral type of M0 while Luhan & Rieke (1999) classify it as earlier than F3. Our spectrum shows broad Hα emission partially filled in with emission as well as an absorption line from OⅠ at 7774 Å characteristic of early-type stars. The strength of the latter plus the absence of an absorption line due to the blend at 6497 Å (BaⅡ, FeⅡ, CaⅠ) leads us to a spectral classification of A0. This spectral classification is in agreement with that derived by McClure et al. (2010).

When combined with the results of Paper I, optical spectra have been obtained for 87% of the stars in the M(I) versus (R−I) diagram that fell above our completeness limit and on or above the 10^7 year old isochrone. A reanalysis of the R− and I-band photometry has led us to revise some of the magnitudes published in Paper I. The revised photometry is presented in Table 4 in the Appendix and used to derive the stellar parameters in this paper.

4.1. Emission-line Spectra

In our previous study, 39 of 131 sources (30%) were found to have strong Hα emission characteristic of CTTS. In this sample, which was not biased toward the detection of Hα emission, 15 sources were found to have EW(Hα) > 10 Å. All of these are newly identified CTTS using this coarse criterion (Herbig & Bell 1988). An additional 17 objects showed weaker Hα emission (10 Å > EW(Hα) > 5 Å) with all but one having an M spectral type. The variable nature of Hα emission is evident when comparing stars observed days apart and stars observed in this study and in Paper I.

4.2. Identification of Pre-main-sequence Association Members

Identification of 35 new PMS objects was accomplished using the same membership criteria as in Paper I with some additional criteria as described below. An additional 13 YSOs with optical spectral types were taken from the literature. Combined with the 87 association members from Paper I, there are a total of 135 objects with optical spectral types that meet one or more of these criteria. These objects are listed in Table 3.9 Ninety percent of the YSOs in our sample have K or M spectral types. The criteria include the following.

1. Hα in emission with EW > 10 Å during at least one observation, characteristic of CTTSs. Fifty-three objects fit this criterion.
2. Association with X-ray emission is a signpost of youth and has been observed in 82 stars in our sample.
3. The presence of lithium absorption is an indicator of youth for stars with spectral type K0 and cooler and clearly resolved in the spectra of 46 stars.
4. A mid-infrared excess as observed by the Infrared Space Observatory (ISO) with a spectral index from 2.2 to 14 μm (Bontemps et al. 2001) or the Spitzer Space Telescope from 3.6 to 24 μm (Wilking et al. 2008) indicative of a circumstellar disk. Thirty-eight objects display a mid-infrared excess.
5. A proper motion in common with the association mean as noted by Mamajek (2008). In addition, we include Object 1-3 from this study as a common proper motion member based on data from the UCAC3 catalog.
6. Two early-type stars, HD 147889 and Source 1, are associated with reflection nebulosity in the R- and I-band images. A proper motion in common with the association mean as noted by Mamajek (2008). In addition, we include Object 1-3 from this study as a common proper motion member based on data from the UCAC3 catalog.
7. Finally, 100 objects (excluding giants identified in Section 3) that are too luminous to be main-sequence objects at the distance to ρ Oph and have an estimate for A_v too high to be foreground to the cloud (A_v > 1.5 mag).

We have noted in Table 3 objects with near-infrared variability from the study of Alves de Oliveira & Casali (2008) but do not require this for association membership. Only one of the objects classified as a possible dwarf based on the CaH index, Object 4-52, displayed a criterion for association membership, and is included in Table 3.

Mamajek (2008) has noted that proper motion data for two of the objects in Table 3, X-ray sources GY 280 and HD 148352, are discordant and are possible foreground objects. Despite this fact, we include them in Table 3 but note that X-ray emission alone may not be sufficient for identifying YSOs.

4.3. Distribution of Association Members

The distribution of the 135 association members identified by this study is shown in Figure 1 relative to contours of 13CO column density which delineate the cloud boundaries (Loren...
Table 2
Optical Properties of Candidate Young Stellar Objects

| F | Ap. | Name(s) | X-Ray ID | R.A.(J2000) | Decl.(J2000) | Li? | EW(Hα) | I | (R−I) | Prev Sp. Ty. | Sp. Ty. | Adopt | Notes |
|---|-----|---------|----------|-------------|--------------|------|--------|---|--------|-------------|---------|-------|-------|
| 3 | 39  | 16 24 39.3 | −24 07 10 | ... | 1.1 | 15.31 | 1.41 | ... | K0-K2 | K1 |       |       |
| 4 | 40  | 16 24 39.7 | −24 35 08 | ... | −9.2 | 15.87 | 2.11 | ... | M4.5 | M4.5 |       |       |
| 4 | 13  | 16 24 40.5 | −24 43 09 | ... | <0.3 | 15.96 | 1.90 | ... | G5-K5 | K0: |       |       |
| 3 | 11  | 16 24 40.7 | −24 21 40 | ... | 0.90 | 14.83 | 1.49 | ... | K0-K2 | K1 |       |       |
| 29 | 29 | 16 24 41.1 | −24 17 49 | ... | > −0.4 | 15.15 | 2.05 | ... | M1-M3 | M2 |       |       |
| 4 | 99  | 16 24 43.9 | −24 47 53 | ... | 0.70 | 14.64 | 1.61 | ... | K3 | K3 |       |       |
| 14 | 14 | 16 24 44.8 | −25 00 18 | ... | −3.5 | 15.74 | 1.64 | ... | M2-M4 | M2 |       |       |
| 3 | 37  | 16 24 46.9 | −24 22 21 | ... | 0.90 | 13.61 | 1.86 | ... | K6-M0 | K7 | Poss. dwarf | |
| 4 | 72  | 16 24 46.9 | −24 22 02 | ... | <0.8 | 13.70 | 1.66 | ... | K2-K5 | K4 |       |       |
| 4 | 2   | UCAC3 | 16 24 47.7 | −24 52 58 | ... | 1.0 | 13.41 | 1.17 | ... | G2-G5 | G5 |       |       |
| 4 | 42  | 16 24 48.1 | −24 40 04 | ... | > −0.4 | 14.80 | 2.14 | ... | M3.5-M7 | M4.5 |       |       |
| 85 | 85 | 16 24 49.3 | −24 28 12 | ... | 1.0 | 14.20 | 1.45 | ... | K0-K5 | K3: |       |       |
| 10 | 10 | 16 24 50.2 | −24 35 39 | ... | 1.3 | 15.39 | 1.66 | ... | G5-K5 | U |       |       |
| 3 | 4   | 16 24 51.6 | −24 17 21 | ... | 0.9 | 14.69 | 1.62 | ... | K1-K3 | K2 |       |       |
| 12 | 12 | 16 24 55.7 | −24 09 15 | ... | 2.0 | 15.01 | 1.26 | ... | G2-G5 | G4 |       |       |
| 4 | 90  | UCAC3 | 16 24 55.8 | −24 53 34 | ... | 1.1 | ... | ... | K3-K6 | K6 |       |       |
| 5 | 58  | 16 24 57.3 | −24 11 23 | Yes | −3.0 | 13.72 | 1.91 | ... | M3.5 (WMR) | M3-M4 | M3.5 |       |
| 4 | 59  | WSB 18 | 16 24 59.7 | −24 55 59 | Yes: | −87 | 13.78 | 1.93 | ... | M2.5-M4.5 | M3.5 |       |       |
| 82 | 82 | WSB 19/UCAC3 | 16 25 02.0 | −24 59 30 | ... | −40 | 13.12 | 1.80 | ... | M3-M5.5 | M4.5 |       |       |
| 3 | 28  | 16 25 03.8 | −24 22 24 | ... | 2.5 | 14.64 | 1.59 | ... | F6-G4 | G0 |       |       |
| 4 | 88  | UCAC3 | 16 25 05.0 | −24 41 09 | ... | 0.80 | 13.47 | 1.58 | ... | K3-K5 | K4 |       |       |
| 3 | 42  | 16 25 05.6 | −24 03 11 | ... | 0.90 | 15.58 | 1.71 | ... | K6-M0 | K7III | Giant |       |
| 14 | 14 | 16 25 07.2 | −23 59 48 | ... | 3.7 | 16.04 | 1.11 | ... | F2-F5 | F3 |       |       |
| 4 | 44  | 16 25 07.9 | −23 58 03 | ... | 1.2 | 14.78 | 1.45 | ... | G5-K0 | G9 |       |       |
| 38 | 38 | 16 25 10.9 | −24 46 03 | ... | −10 | 15.78 | 2.20 | ... | M4-M6 | M5 |       |       |
| 3 | 32  | 16 25 11.9 | −24 37 07 | ... | 0.80 | 14.78 | 1.79 | ... | K5-K6 | K6 |       |       |
| 3 | 31  | 16 25 12.3 | −23 58 31 | ... | 0.80 | 14.71 | 1.41 | ... | K1-K3 | K2 |       |       |
| 3 | 17  | 16 25 16.8 | −24 04 41 | ... | 0.80 | 15.37 | 1.50 | ... | K3 | K3 |       |       |
| 27 | 27 | 16 25 17.0 | −24 11 44 | ... | 0.80 | 14.36 | 2.25 | ... | M3-M4.5 | M4.5III | Giant |       |
| 4 | 52  | 16 25 18.9 | −24 47 59 | Yes: | −12 | 14.98 | 2.17 | ... | M2-M4 | M3 | Pos. dwarf |       |
| 4 | 91  | UCAC3 | 16 25 22.9 | −24 57 18 | ... | 0.70 | 12.74 | 1.27 | ... | K3-K5 | K3 |       |       |
| 3 | 26  | 16 25 23.1 | −24 42 08 | ... | 0.95 | 14.79 | 1.46 | ... | K1-K5 | K3 |       |       |
| 3 | 6   | 16 25 23.6 | −24 22 54 | ... | 1.6 | 15.61 | 1.63 | ... | G4-G9 | G5 |       |       |
| 3 | 35  | 16 25 24.1 | −23 56 56 | ... | −1.6 | 15.18 | 1.67 | M3 (WMR) | M3-M4 | M3.5 | Poss. dwarf |       |
| 3 | 34  | 16 25 25.6 | −24 07 28 | ... | 1.2 | 15.19 | 1.65 | ... | G9-K0 | K0 |       |       |
| 6 | 42  | Same as 3-34 | ... | <2 | 15.67 | 1.66 | ... | G5-K5 | G7 |       |       |
| 3 | 30  | 16 25 26.3 | −23 23 56 | ... | 1.3 | 14.50 | 1.85 | ... | K0-K2 | K2 |       |       |
| 3 | 45  | 16 25 26.3 | −24 01 06 | ... | 0.90 | 14.28 | 1.48 | ... | K0-K2 | K2 |       |       |
| 3 | 2   | UCAC3 | 16 25 27.0 | −24 20 50 | ... | 0.70 | 15.66 | 1.74 | ... | K3-K4 | K4 |       |       |
| F | Ap. | Name(s) | X-Ray ID | R.A.(J2000) (hhmm.s) | Decl.(J2000) (°, ′) | Li? | EW(Hα) | I | (R–I) | Prev Sp. Ty. | Sp. Ty. | Adopt | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6 | 76 | | | 16 25 28.8 | -24 22 59 | ... | <0.1 | 15.14 | 1.51 | M3.25 (WMR) | U | M3.25 | |
| 4 | 65 | UCAC3 | | 16 25 29.9 | -24 39 14 | ... | -0.30 | 14.15 | 1.22 | M2 (WMR) | M1-M3 | M2 | Poss. dwarf |
| 62 | 16 25 31.6 | -24 21 22 | ... | <0.2 | 17.03 | 1.61 | K1.5 (WMR) | ... | K7-M3 | M0 | |
| 4 | 17 | | | 16 25 32.3 | -24 19 59 | > -3.5 | 15.63 | 1.60 | ... | K7-M3 | M0 | |
| 58 | 16 25 34.1 | -24 36 32 | ... | <0.5 | 14.81 | 1.45 | ... | U | U | |
| 3 | 50 | GSS 15 | | 16 25 35.6 | -24 34 00 | ... | 0.80 | 13.39 | 2.27 | ... | M3-M4.5 | M4III | Giant |
| 98 | 16 25 36.1 | -24 00 26 | ... | > -0.2 | 13.65 | 1.20 | ... | K2-K6 | K5 | |
| 3 | 5 | | | 16 25 36.2 | -24 04 04 | ... | 0.90 | 15.15 | 1.92 | ... | K5.5-K8 | K6: | |
| 56 | ISO-Oph 1/WLY 2-2/UCAC3 | | | 16 25 36.8 | -24 15 42 | Yes | -2.8 | 13.36 | 1.58 | K3.5 (LR) | K3-K5 | K4 | |
| 49 | | | | 16 25 37.8 | -24 13 43 | ... | <0.2 | 13.57 | 2.46 | M4.25III (WMR) | M3.5-M5 | M4.25III | Giant |
| 1 | 29 | | | 16 25 37.9 | -24 43 05 | ... | 0.70 | 14.71 | 1.41 | ... | K2-K4 | K3 | |
| 40 | | | | 16 25 44.2 | -24 33 02 | ... | > -0.5 | 16.09 | 2.13 | ... | K2-K4 | K3 | |
| 16 | UCAC3 | ROX3 | | 16 25 49.6 | -24 51 30 | Yes | -2.4 | 11.03 | 1.01 | K3/M0 (BA) | M6-M1 | K8 | |
| 1 | 3 | UCAC3 | | 16 25 50.5 | -24 47 34 | ... | 1.0 | 13.47 | 1.42 | ... | G9-K0 | K0 | |
| 28 | | | | 16 25 51.0 | -24 34 55 | ... | <0.2 | 16.38 | 2.10 | ... | K4 | K4 | |
| 44 | Same as 1-28 | | | 16 25 52.5 | -24 04 19 | Yes: | 0.70 | 16.02 | 1.10 | F9.5 (WMR) | G5-K5 | G9 | |
| 6 | 5 | | | 16 25 57.5 | -24 42 07 | ... | 1.0 | 14.40 | 1.62 | ... | K0-K2 | K2 | |
| 1 | 15 | | | 16 25 57.6 | -24 41 00 | ... | 0.70 | 15.34 | 1.60 | ... | K0-K2 | K1 | |
| 1 | 16 | | | 16 25 58.9 | -24 52 47 | Yes: | -7.3 | 13.86 | 1.92 | M4.5 (WMR) | M2-M4 | M4 | |
| 3 | 9 | | | 16 26 02.2 | -24 02 04 | ... | 0.60 | 13.76 | 1.87 | ... | M2.5-M4 | M3III | Giant |
| 53 | | | | 16 26 03.0 | -24 08 48 | ... | 3.7 | 14.73 | 1.44 | ... | F2-F4 | F3 | |
| 20 | UCAC3 | | | 16 26 09.1 | -24 01 29 | ... | 1.0 | 13.81 | 1.36 | ... | K0-K3 | K2 | |
| 4 | 11 | UCAC3 | | 16 26 10.9 | -24 52 14 | ... | 1.0 | 12.52 | 1.18 | ... | G9-K3 | K1 | |
| 10 | UCAC3 | | | 16 26 16.9 | -24 00 07 | ... | 1.0 | 13.36 | 1.26 | ... | K0-K3 | K2 | |
| 43 | GSS 29 | ROXC J162616.8-242224 | | 16 26 16.9 | -24 22 23 | Yes: | -2.6 | 15.23 | 2.17 | K6 (LR) | K5-K6 | K6 | |
| 93 | Same as 3-43 | | | 16 26 18.7 | -24 07 19 | Yes: | > -2.5 | 15.18 | 1.80 | M3.25 (WMR) | M3-M3.5 | M3.25 | |
| 6 | 2 | Same as 3-43 | | 16 26 18.8 | -24 12 25 | ... | 1.1 | 15.44 | 1.82 | ... | K1-K3 | K2 | |
| 15 | UCAC3 | RXJ1626.3-2407? | | 16 26 22.5 | -23 58 19 | ... | > -1.0 | 16.12 | 1.32 | K4 (WMR) | K6 | K6 | |
| 23 | GSS 32/Source 2 | ROXC J162624.0-242449 | | 16 26 24.1 | -24 24 48 | ... | -7.6 | 15.58 | 2.23 | K8 (LR) | K5-K6 | K5 | |
| 3 | 51 | | | 16 26 24.3 | -24 01 16 | ... | -11 | 15.84 | 2.11 | M4.5 (WMR) | M3-M5.5 | M4.5 | |
| 31 | | | | 16 26 29.2 | -24 48 15 | ... | 1.3 | 16.46 | 1.04 | G0 (WMR) | F6-G3 | G0 | |
| 25 | | | | 16 26 35.5 | -24 55 58 | ... | > -0.4 | 16.00 | 1.58 | ... | K1-K3 | K3 | |
| 16 | ISO-Oph 51 | ROXC J162636.8-241552 | | 16 26 37.0 | -24 15 52 | Yes: | -9.6 | 15.67 | 1.70 | ... | K7-M1 | M0 | |
| 26 | AOC 88 | | | 16 26 37.5 | -24 08 42 | ... | 0.80 | 16.01 | 1.79 | ... | K2-K4 | K3 | |
| 18 | GSS 37/VSSG 2 | ROXC J162642.8-242030 | | 16 26 42.9 | -24 20 30 | ... | -10 | 14.33 | 1.99 | K6 (MMGC), M0 (LR) | K7-M2 | M1 | |
| 33 | UCAC3 | ROXC J162643.2-241109 | | 16 26 43.1 | -24 11 09 | Yes: | -1.0 | 13.32 | 1.51 | K8 (WMR) | K7-M0 | K8 | |
| 21 | | | | 16 26 43.5 | -24 52 23 | ... | 0.80 | 14.33 | 1.39 | ... | K6-K7 | K6 | |
| F | Ap. | Name(s) | X-Ray ID | R.A.(J2000) (hh:mm:ss) | Decl.(J2000) (°/′/) | Li? | EW(Hα) (mag) | I (mag) | (R−I)² (mag) | Prev Sp. Ty. | Sp. Ty. | Adopt | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 22 | ROXN 6 | | 16 26 44.4 | −24 47 13 | Yes | −4.0 | 13.92 | 1.79 | M4.5 (WMR) | M3-M4 | M4 |
| | 36 | ROXN 9 | | 16 26 46.1 | −23 58 10 | . . | -3.8 | 15.53 | 2.11 | M3 (WMR) | M2-M4 | M3 |
| | 4 | Same as 1-8 | | | | | | | | M5 | M5/M6 |
| 5 | AOC 64 | | | 16 26 50.5 | −24 13 52 | Yes | −6.2 | 14.79 | 2.02 | M4.5 (WMR) | M3-M4 | M3.5 |
| 6 | Same as 2-56 | | | | | Yes | −5.8 | | | M3-M4 |
| 7 | 10 | | | 16 26 53.2 | −24 05 58 | ... | < −0.4 | 16.92 | 1.48 | K0.5 (WMR) | U | K0.5 |
| 8 | 24 | | | 16 26 53.7 | −24 01 55 | ... | 1.6 | 15.78 | 1.77 | ... | G5-K2 | G9 |
| 9 | 85 | Same as 3-24 | | | | ... | > −3.0 | | | | | |
| 10 | UCAC3 | | | 16 26 55.0 | −24 10 16 | ... | 0.2 | 13.84 | 1.44 | M3 (WMR) | M2-M4 | M3 |
| 11 | 1 | | | 16 26 57.4 | −24 49 48 | ... | 0.70 | 15.78 | 1.78 | ... | K4-K5 | K5 |
| | 4 | | | 16 26 57.8 | −24 52 37 | ... | < 0.5 | 17.48 | 0.98 | K5 (WMR) | G2-K6 | K5 |
| 12 | ROX J162704.0-240932 | | | 16 27 04.2 | −24 09 32 | Yes | −4.1 | 14.06 | 1.68 | M2 (MMGC) | M0-M2 | M1 |
| 13 | 7 | Same as 2-32 | | | | Yes | −5.2 | | | M0-M2 |
| 14 | 51 | | | 16 27 04.5 | −24 03 28 | ... | 0.90 | 13.97 | 1.60 | ... | K0-K3 | K2.5 |
| 15 | 41 | Same as 2-51 | | | | ... | 0.90 | | | K1-K3 |
| 16 | 5 | ISO-Oph 97/GY 194 | | 16 27 04.6 | −24 42 13 | Yes: | −2.6 | 15.66 | 1.88 | ... | K8-M0 | M0 |
| 17 | 67 | | | 16 27 04.6 | −24 42 58 | Yes | −3.5 | 14.97 | 1.72 | ... | K6-M1 | K8 |
| 18 | 29 | | | 16 27 06.6 | −24 07 03 | ... | −4.3 | 15.36 | 2.18 | M4.5 (WMR) | M3-M5 | M4.5 |
| 19 | 46 | Same as 2-29 | | | | ... | −12 | | | M3-M5.5 |
| 20 | 57 | ISO-Oph 106 | | 16 27 09.1 | −24 12 01 | ... | −12 | 16.16 | 2.29 | M2.5 (WMR) | U | M2.5 Poss. dwarf |
| 21 | 81 | Same as 3-57 | | | | ... | −50 | 15.33 | 1.90 | M0 (MMGC) | K4-K5 | K6 |
| 22 | 23 | ROX J162711.8-241031 | | 16 27 12.0 | −24 10 31 | Yes | −0.50 | 15.33 | 1.90 | M0 (MMGC) | K4-K5 | K6 |
| 23 | 54 | Same as 2-23 | | | | ... | > −1.5 | | | K4-K6 |
| 24 | 58 | Same as 2-23 | | | | Yes | > −1.0 | | | K6-M2 |
| 25 | 38 | Same as 2-23 | | | | ... | −1.7 | | | K6 |
| 26 | 6 | WSB 47 | | 16 27 17.0 | −24 47 11 | ... | 0.70 | 15.08 | 1.76 | K1 (WMR) | K2-K5 | K2 |
| 27 | 54 | Same as 1-6 | | | | ... | 0.70 | 13.67 | 1.67 | ... | K1-K3 | K3 |
| 28 | 61 | UCA C3 | | 16 27 17.1 | −24 06 48 | ... | 0.90 | 13.67 | 1.67 | ... | K1-K3 | K3 |
| 29 | 22 | Same as 2-61 | | | | ... | 0.80 | | | K2-K3 |
| 30 | 62 | | | 16 27 18.0 | −23 58 46 | ... | 0.80 | 13.20 | 1.62 | ... | K7-K8 | K8 |
| 31 | 82 | | | 16 27 18.1 | −24 53 16 | ... | −9.0 | 16.63 | 2.02 | M2.5 (WMR) | M0-M5 | M2.5 Poss. dwarf |
| 32 | 17 | | | 16 27 20.4 | −23 58 42 | ... | < −0.2 | 17.40 | 1.34 | U (WMR) | M0-M3 | M1 |
| 33 | 21 | | | 16 27 25.2 | −23 55 54 | ... | 1.0 | 13.41 | 1.34 | ... | K2-K3 | K2 |
| 34 | 40 | | | 16 27 28.9 | −24 09 38 | ... | 2.8 | 14.85 | 1.48 | ... | F2-F4 | F3.5 |
| 35 | 38 | Same as 2-40 | | | | ... | 2.9 | | | F2-F5 |
| 36 | 13 | ISO-Oph 149 | | 16 27 30.9 | −24 47 26 | ... | −7.2 | 16.17 | 2.15 | ... | M1-M2 | M1 |
| 37 | UCA C3 | | | 16 27 31.3 | −23 59 09 | ... | 0.30 | 13.12 | 1.02 | M1 (WMR) | M0-M1 | M1 |
| 38 | 17 | ISO-Oph 155/GY 292 | | 16 27 33.2 | −24 41 14 | ... | −60 | 15.65 | 2.01 | K8 (LR) | K5-K6 | K6 |
| 39 | 59 | Same as 1-17 | | | | ... | −80 | | | K6-M0 |
| F | Ap. | Name(s) | X-Ray ID | R.A.(J2000) (h:m:m:s) | Decl.(J2000) (°:°') | Li? | EW(Hα) | I (R−I)² | Prev Sp. Ty. | Sp. Ty. | Adopt | Notes |
|---|-----|---------|----------|----------------------|---------------------|-----|---------|---------|-------------|---------|--------|-------|
| 1 | 7   | GY 297  |          | 16 27 36.5           | −24 28 33           | ... | <0.2   | 13.32  | 1.35        | M2 (WMR) | M2-M3  | M3    |
| 2 | 46  | Same as 1-7 |        | 16 27 37.3           | −24 30 34           | ... | <0.2   | 14.67  | 1.99        | M0 (G)  | B5-F2  | A0    |
| 5 | 88  | Same as 1-7 |        | 16 27 38.0           | −23 57 24           | Yes | −2.8   | 13.73  | 1.72        | M2.5 (WMR) | M1-M3  | M2.5  |
| 6 | 18  | Same as 1-7 |        | 16 27 38.5           | −24 04 02           | Yes | −1.4   | 13.41  | 1.58        | ...      | K5-K6  | K5.5  |
| 7 | 1   | WLY 2-48/ISO-Oph 159 | | 16 27 43.6           | −24 51 25           | 1.0  | 14.26  | 1.51   | ...      | K1-K2  | K2     |
| 8 | 14  |          |          | 16 27 45.2           | −25 03 33           | Yes | −0.7   | 14.07  | 1.85        | M4.5 (WMR) | M3-M5  | M3.5  |
| 9 | 79  |          |          | 16 27 49.3           | −23 56 09           | <0.8 | 16.30  | 1.04   | ...      | G2.5 (WMR) | F6-K0  | G2.5  |
| 10| 2   | UCAC3   | ROXC J162738.2-240401 | 16 27 54.4           | −24 51 60           | 0.70 | 13.63  | 1.27   | ...              | ...     | K3-K5  | K4    |
| 11| 23  |          |          | 16 27 59.7           | −23 57 16           | >0.4  | 17.01  | 1.74   | ...      | M0 (WMR) | K8-M0  | M0    |
| 12| 30  |          |          | 16 28 00.8           | −24 00 52           | Yes  | −3.8   | 13.90  | 1.84        | M3 (WMR) | M2-M2  | M2    |
| 13| 27  |          |          | 16 28 01.4           | −24 02 11           | 1.1   | 14.62  | 1.48   | ...      | G5-K0  | G9     |
| 14| 2   | UCAC3   |          | 16 28 02.2           | −24 19 05           | 3.3   | 15.31  | 1.66   | ...      | F1-F3.5 | F2     |
| 15| 11  |          |          | 16 28 03.4           | −24 53 22           | Yes  | −9.2   | 14.41  | 2.11        | ...      | M5-M6  | M5.5  |
| 16| 78  |          |          | 16 28 04.9           | −23 56 08           | 1.1   | 17.28  | 1.22   | ...      | K5 (WMR) | G5-K2  | G9    |
| 17| 21  |          |          | 16 28 05.9           | −24 29 12           | 0.90  | 15.48  | 1.79   | ...      | K0-K2  | K1     |
| 18| 12  |          |          | 16 28 06.6           | −24 18 55           | 2.4   | 14.79  | 1.48   | ...      | F7-G4  | G0     |
| 19| 43  | UCAC3   |          | 16 28 08.1           | −24 04 49           | 0.80  | 13.36  | 1.58   | ...      | K1-K4  | K3     |
| 20| 41  |          |          | 16 28 09.9           | −24 48 48           | >0.4  | 16.68  | 0.86   | K4.5 (WMR) | K0-K5  | K4.5   |
| 21| 98  |          |          | 16 28 11.0           | −24 55 57           | >0.4  | 15.92  | 2.00   | ...      | K0-K5  | K3     |
| 22| 18  |          |          | 16 28 11.1           | −24 06 18           | Yes  | −6.3   | 14.29  | 2.10        | M3.75 (WMR) | M3-M4.5 | M3.75  |
| 23| 22  |          |          | 16 28 11.2           | −24 29 19           | 0.80  | 15.44  | 1.70   | ...      | G9-K0  | G9     |
| 24| 62  |          |          | 16 28 12.3           | −24 09 28           | 0.90  | 13.37  | 2.26   | ...      | M2.5-M4 | M3.5III | Giant |
| 25| 17  | Same as 2-62 |        | 16 28 13.9           | −24 32 49           | ...   | <11    | 15.72  | 2.36        | ...      | M2.5-M4.5 | M3-M4 |
| 26| 34  | Same as 2-62 |        | 16 28 13.9           | −24 36 10           | Yes  | −3.5   | 14.13  | 1.45        | ...      | K7-M0  | M0    |
| 27| 7   | ISO-Oph 194 | ROXC J162813.7-243249 | 16 28 14.4           | −23 57 52           | >0.4  | 17.53  | 1.12   | G7 (WMR) | G0-K5  | G7     |
| 28| 26  | AOC 7    |          | 16 28 14.9           | −24 23 22           | 2.3   | 15.32  | 1.71   | ...      | G9-K2  | K0     |
| 29| 39  |          |          | 16 28 15.8           | −24 09 32           | 1.1   | 15.73  | 1.78   | ...      | G9-K2  | K0     |
| 30| 94  |          |          | 16 28 16.6           | −20 07 36           | >0.2  | 16.79  | 1.67   | U (WMR) | U       | U      | M0    |
| 31| 7   | Same as 5-94 |        | 16 28 16.6           | −20 07 36           | <0.3  | ...    | ...    | ...            | K6-M1  | ...    |
| 32| 10  | ISO-Oph 195 | RXJ 1628.2-2405 | 16 28 16.9           | −24 05 15           | Yes  | <3.4   | 13.91  | 1.68        | K5 (MMGC) | K5-K6  | K6    |
| 33| 1   |          |          | 16 28 17.6           | −24 33 54           | 1.0   | 15.30  | 1.97   | ...      | K3-K5  | K3     |
| 34| 91  | Same as 1-32 |        | 16 28 18.8           | −24 20 15           | <0.2  | 15.01  | 2.00   | ...      | M0-M5  | M1III  | Giant |

**Notes:**
- M2 (WMR): M2 spectral type with weak magnetic field.
- M2-M3: M2 to M3 spectral types.
- M3: M3 spectral type.
- M4: M4 spectral type.
- M2.5-M4: M2.5 to M4 spectral types.
- K6-M1: K6 to M1 spectral types.
- M2.5-M4.5: M2.5 to M4.5 spectral types.
- M3-M4.5: M3 to M4.5 spectral types.
- M3.5III: M3.5 III spectral type.
- Giant: Giant spectral type.
### Table 2 (Continued)

| F | Ap. | Name(s) | X-Ray ID | R.A.(J2000) (hhmmss.s) | Decl.(J2000) (° ′ ″) | Li? | EW(\(\alpha\)) | I | \((R-I)\) | Prev Sp. Ty. | Sp. Ty. | Adopt | Notes |
|---|-----|---------|----------|------------------------|----------------------|-----|--------------|---|-----------|-------------|---------|--------|-------|
| 5 | 62  | Same as 2-53 |         | 16 28 20.0 | −24 26 11 | ... | > 0.2 | 15.70 | 1.20 | G5 (WMR) | U | G5   |       |
| 5 | 59  | U        |         | 16 28 20.1 | −24 23 18 | ... | −4.2 | 15.65 | 2.04 | M5.5 (WMR) | ... | ... |       |
| 5 | 16  | U        |         | 16 28 21.5 | −24 48 15 | 0.70 | ... | 15.09 | 1.55 | ... | ... | ... |       |
| 2 | 6   | ROXC J162821.5-242155 | | 16 28 21.6 | −24 21 55 | Yes | −3.3 | 14.99 | 1.98 | M2.5 (WMR) | ... | ... |       |
| 2 | 41  | U        |         | 16 28 21.7 | −24 17 45 | ... | 1.5  | 15.29 | 1.65 | ... | F9-G4 | G1  |       |
| 1 | 10  | U        |         | 16 28 23.0 | −24 48 28 | ... | −14 | 15.74 | 2.10 | ... | ... | ... | M3.5-M5 |
| 2 | 9   | U        |         | 16 28 24.8 | −24 08 14 | ... | 1.2  | 16.53 | 1.54 | ... | K4-K6 | K4: |       |
| 6 | 33  | Same as 2-9 |         | 16 28 24.9 | −24 35 43 | Yes | −9.0 | 14.80 | 1.98 | M5 (WMR) | ... | ... |       |
| 1 | 26  | U        |         | 16 28 28.3 | −24 52 22 | 0.50 | 15.03 | 1.37 | K6 (WMR) | ... | ... |       |
| 5 | 12  | U        |         | 16 28 28.3 | −23 58 51 | ... | 2.0  | 17.04 | 1.31 | U (WMR) | ... | ... |       |
| 5 | 49  | U        |         | 16 28 29.4 | −24 31 21 | ... | <0.1 | 16.57 | 1.20 | K0 (WMR) | ... | ... |       |
| 6 | 37  | Same as 5-49 |         | 16 28 31.2 | −24 02 34 | ... | 0.6  | 14.41 | 1.93 | ... | K4-K6 | K5: |       |
| 2 | 37  | U        |         | 16 28 32.4 | −24 05 49 | ... | −6.4 | 15.44 | 2.35 | ... | M3-M4 | M3.5 |       |
| 2 | 45  | U        |         | 16 28 32.6 | −24 15 24 | ... | −11 | 15.97 | 2.33 | M3.5 (WMR) | ... | ... |       |
| 5 | 84  | U        |         | 16 28 36.3 | −20 44 03 | ... | <1.0 | 16.31 | 1.53 | K1 (WMR) | ... | ... |       |
| 6 | 56  | Same as 5-84 |         | 16 28 43.1 | −24 22 52 | Yes | −6.8 | 14.47 | 2.07 | M4.75 (WMR) | ... | ... |       |
| 2 | 16  | U        |         | 16 28 43.5 | −24 52 18 | 1.3  | 12.97 | 1.08 | ... | K0-K4 | K2  |       |
| 5 | 51  | U        |         | 16 28 43.6 | −24 04 44 | 1.7  | 15.77 | 1.25 | G0 (WMR) | ... | ... |       |
| 4 | 47  | U        |         | 16 28 43.9 | −24 06 41 | 0.9  | 14.32 | 1.80 | ... | K6-M0 | M0III | Giant |
| 5 | 7   | AOC 27   |         | 16 28 47.2 | −24 28 13 | ... | −190 | 16.00 | 2.05 | ... | M3.5-M5.5 | M4.5 |       |
| 7 | 4   | UCAC3    |         | 16 28 48.6 | −24 04 41 | <0.6 | 16.74 | 1.41 | ... | F0-G9 | G0: |       |
| 5 | 50  | Same as 5-74 |         | 16 28 49.8 | −23 55 08 | ... | 1.9  | 15.17 | 1.65 | ... | F6-G9 | K6  |       |
| 2 | 54  | Same as 2-54 |         | 16 28 51.6 | −24 06 11 | ... | >0.2 | 15.37 | 1.31 | ... | G2-G4 | G3  |       |
| 5 | 25  | U        |         | 16 28 52.1 | −24 47 39 | 0.80 | 13.62 | 1.70 | ... | K3-K5 | K2  |       |
| 5 | 97  | UCAC3    |         | 16 28 52.1 | −24 47 39 | ... | 1.0  | 15.44 | 1.65 | ... | K3-K6 | K3: |       |
| 5 | 20  | AOC 73   |         | 16 28 56.9 | −24 38 10 | 1.0  | 15.44 | 1.65 | ... | K3-K6 | K3: |       |
| 4 | 4   | AOC 40   | ROXC J162856.8-243109 | 16 28 57.1 | −24 31 09 | ... | −52 | 15.39 | 2.08 | ... | M5-M6 | M5.5 |       |
| 2 | 50  | WSB 65   |         | 16 28 58.9 | −24 04 23 | 1.5  | 14.52 | 1.44 | ... | G3-G5 | G4  |       |
| 9 | 93  | WSB 59   |         | 16 28 59.2 | −24 05 16 | ... | −0.4 | 17.05 | 1.69 | G2.5 (WMR) | ... | ... |       |
| 6 | 9   | Same as 5-93 |         | 16 29 00.0 | −24 26 39 | ... | −1.0 | 15.24 | 0.96 | G9 (WMR) | ... | ... |       |
| 4 | 36  | U        |         | 16 29 02.0 | −23 56 23 | ... | <0.4 | 14.46 | 2.00 | G9 (WMR) | ... | ... |       |
| 2 | 53  | U        |         | 16 29 02.0 | −23 56 23 | ... | −0.2 | 17.43 | 0.89 | G7.5 (WMR) | ... | ... |       |
| 2 | 57  | U        |         | 16 29 03.1 | −24 27 49 | ... | −12 | 13.19 | 1.95 | ... | M3.5-M5.5 | M5  |       |
| 6 | 31  | Same as 2-57 |         | 16 29 03.1 | −24 27 49 | ... | −12 | 13.19 | 1.95 | ... | M3.5-M5.5 | M5  |       |
| F | Ap.a | Name(s)b | X-Ray IDc | R.A.(J2000) (hhmmss.s) | Decl.(J2000) (° ’ ″) | Li? | EW(Hα) (mag) | R−I| Prev Sp. Ty.e | Sp. Ty. | Adopt | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 96 | UCAC3 | | 16 29 03.7 | −24 30 02 | ... | <0.5 | 16.55 | 1.70 | ... | M2-M4 | M3 |
| 6 | 6 | UCAC3 | | 16 29 06.9 | −23 55 16 | ... | 1.6 | 13.97 | 1.44 | ... | K1-K3 | K2 |
| 5 | 25 | Same as 5-25 | | 16 29 11.6 | −24 22 15 | ... | > −0.1 | 17.79 | 1.09 | G0.5 (WMR) | F0-K5 | G0.5 |
| 6 | 77 | Same as 5-25 | | 16 29 33.8 | −24 43 54 | ... | > −0.8 | 17.52 | 0.83 | K1 (WMR) | U | K1 |
| 5 | 34 | UCAC3 | | 16 29 39.9 | −24 29 11 | ... | <0.2 | 16.15 | 0.97 | G5 (WMR) | U | G5 |
| 5 | 24 | UCAC3 | | 16 29 45.2 | −24 30 55 | ... | > −0.3 | 17.66 | 0.87 | G2.5 (WMR) | G0-M0 | G2.5 |
| 2 | 8 | UCAC3 | | 16 29 46.4 | −24 09 01 | ... | 0.90 | 14.36 | 1.43 | ... | G8-K0 | G9 |
| 5 | 33 | UCAC3 | | 16 29 46.9 | −24 06 48 | ... | 1.0 | 14.12 | 1.45 | ... | K0-K2 | K1 |
| 5 | 31 | Same as 5-25 | | 16 29 25.6 | −23 49 35 | ... | 1.0 | 13.97 | 1.78 | ... | K1-K5 | K3 |
| 2 | 14 | Same as 5-25 | | 16 29 27.2 | −23 49 18 | ... | <0.2 | 16.00 | 1.49 | ... | M2-M3 | M3 |
| 5 | 17 | Same as 5-25 | | 16 29 28.7 | −24 21 26 | ... | 2.1 | 15.85 | 0.83 | ... | F7-G4 | G0 |
| 4 | 49 | Same as 5-25 | | 16 29 32.2 | −24 05 49 | ... | 0.80 | 14.30 | 1.40 | ... | K1-K3 | K3 |
| 5 | 77 | Same as 5-25 | | 16 29 32.5 | −24 36 06 | ... | <0.2 | 14.78 | 1.63 | ... | K4-K5 | K5 |

Notes.

a HYDRA field and aperture number of observation.
b Sources names from optical or infrared studies by (GSS, Source 2) Grasdalen et al. 1973; (VSSG) Vrba et al. 1975; (VSS) Vrba et al. 1976; (WSB) Wilking et al. 1987; (WLY) Wilking et al. 1989; (GY) Greene & Young 1992; (ISO-Oph) Bontemps et al. 2001; (AOC) Alves de Oliveira & Casali 2008; and (UCAC3) Zacharias et al. 2009.
c X-ray source association from the EINSTEIN survey by (ROX) Montmerle et al. 1983, the ROSAT surveys by (RXJ) Martín et al. 1998 and (ROXRF) Grosso et al. 2000, the Chandra surveys by ([IKT2001]) Imanishi et al. 2001 and (ROXC) N. Grosso 2005, private communication, or the XMM-Newton survey by (ROXN) Ozawa et al. 2005.
d R- and I-band photometry from this study except for ROX 3 which are from S. Gordon & K. M. Strom 1990, unpublished data.
e References for spectral types: (BA) Bouvier & Appenzeller 1992; (MMGC) Martín et al. 1998; (LR) Luhman & Rieke 1999; (WMR) Wilking et al. 2005; (G) Geers et al. 2007.
| F | Ap.  | Name(s)* | WMRb | Sp. Typec | $A_v$ d | $M(I)$  | $\log T_{eff}$ | $\log (L/L_\odot)$ | $M_*/(M_\odot)$ | $\log(\text{age})$ (yr) | Criteriaf | Notesg |
|---|------|----------|------|-----------|--------|----------|----------------|-------------------|-------------------|-------------------|------------|-------|
| 4  | 40   | M4.5     | 2.1  | 9.03      | 3.488  | -1.79    | 0.15          | 7.18              | ext               |                  |           |       |
| 4  | 29   | M2       | 5.6  | 6.23      | 3.544  | -0.82    | 0.32          | 6.46              | ext               |                  |           |       |
| 3  | 37   | K7       | 6.8  | 3.96      | 3.602  | 0.06     | 0.42          | 5.65              | ext               |                  |           |       |
| 4  | 42   | M4.5     | 2.3  | 9.85      | 3.488  | -1.31    | 0.16          | 6.57              | ext               |                  |           |       |
|    |      | RXJ 1624.9-2459 |   |           |        |          |               |                  |                   |                   |           |       |
| 3  | 58   | K5 (MMGC) | 0.3 (2M) | 6.91 | 3.638  | -1.44    |               |                  |                  | pm,x              |           |       |
| 4  | 59   | WSB 18   |      |           |        |          |               |                  | ext,ha,IRX        |                  |           |       |
| 4  | 82   | WSB 19   |      |           |        |          |               |                  | ha,IRX            |                  |           |       |
| 3  | 38   | M5       | 1.8  | 9.13      | 3.477  | -1.78    | 0.12          | 7.01              | ext,ha            |                  |           |       |
| 4  | 32   | K6       | 7.0  | 5.03      | 3.621  | -0.40    | 0.73          | 6.61              | ext               |                  |           |       |
| 4  | 52   | M3       | 5.0  | 6.40      | 3.525  | -0.85    | 0.23          | 6.27              | ext,ha            |                  |           |       |
|    |      | GSS 5    |      |           |        |          |               |                  | ext,ha,IRX        |                  |           |       |
| 4  | 59   | M4.5     | 0.0 (GS) | 7.31 | 3.488  | -1.10    | 0.16          | 6.31              | pm,x              |                  |           |       |
|    |      | SR 22    |      |           |        |          |               |                  | ha,IRX            |                  |           |       |
|    |      | HD 147889 |      |           |        |          |               |                  | ha,IRX            |                  |           |       |
| 4  | 16   | GSS 20   |      |           |        |          |               |                  | ext,pm,neb        |                  |           |       |
| 4  | 35   | GSS 22   |      |           |        |          |               |                  | ext,pm,neb        |                  |           |       |
| 4  | 45   | ROXRI-1/SR 8 | 1.6 (2M) | 3.81 | 3.602  | -0.18    | 0.49          | 5.98              | pm,ref.x          |                  |           |       |
| 4  | 17   | M4       | 4.3  | 7.49      | 3.580  | -1.34    | 0.52          | 7.98              | ext               |                  |           |       |
| 3  | 5    | K6       | 7.8  | 4.92      | 3.621  | -0.35    | 0.70          | 6.51              | ext,ha,IRX        |                  |           |       |
| 3  | 56   | WLY 2-2  | 6.7  | 3.79      | 3.662  | 0.12     | 0.80          | 6.08              | ext,ha,IRX        |                  |           |       |
| 3  | 56   | WLY 2-3  | 3-15 | M2       | 4.8    | 6.42    | 3.544        | -0.90             | 0.32              | 6.58              | ext,ha,IRX        |                  |       |
|    |      | WLY 2-2  | 2-32 | M3.5     | 2.5    | 7.20    | 3.512        | -1.14             | 0.21              | 6.54              | ext,ha,IRX        |                  |       |
| 4  | 16   | ROX 3    | 1.1 (GS) | 8.27 | 3.591  | -0.28    | 0.47          | 6.06              | pm,x              |                  |           |       |
| 4  | 45   | VSS 23   | 4.4 (C) | -1.76 | 4.320  | 3.63    | 8.3           |                  | ext,ha,IRX        |                  |           |       |
|    |      | VSS 23   | 1-22 | K5.5     | 5.0    | 3.81    | 3.630        | 0.10              | 5.76              | pm,ref.x          |                  |       |
| 4  | 45   | K0       | 6.6  | 3.96      | 3.720  | 0.11     | 1.3           | 6.95              | ext,pm,neb        |                  |           |       |
|    |      | ROXRI-1/SR 8 | 1.6 (2M) | 3.81 | 3.602  | -0.18    | 0.49          | 5.98              | pm,ref.x          |                  |           |       |
| 4  | 17   | M4       | 4.3  | 7.49      | 3.580  | -1.34    | 0.52          | 7.98              | ext,ha,IRX        |                  |           |       |
| 3  | 5    | K6       | 7.8  | 4.92      | 3.621  | -0.35    | 0.70          | 6.51              | ext,ha,IRX        |                  |           |       |
| 3  | 56   | WLY 2-2  | 6.7  | 3.79      | 3.662  | 0.12     | 0.80          | 6.08              | ext,ha,IRX        |                  |           |       |
| 3  | 56   | WLY 2-3  | 3-15 | M2       | 4.8    | 6.42    | 3.544        | -0.90             | 0.32              | 6.58              | ext,ha,IRX        |                  |       |
|    |      | WLY 2-2  | 2-32 | M3.5     | 2.5    | 7.20    | 3.512        | -1.14             | 0.21              | 6.54              | ext,ha,IRX        |                  |       |
| 4  | 16   | ROX 3    | 1.1 (GS) | 8.27 | 3.591  | -0.28    | 0.47          | 6.06              | pm,x              |                  |           |       |
| 4  | 45   | VSS 23   | 4.4 (C) | -1.76 | 4.320  | 3.63    | 8.3           |                  | ext,ha,IRX        |                  |           |       |
|    |      | VSS 23   | 1-22 | K5.5     | 5.0    | 3.81    | 3.630        | 0.10              | 5.76              | pm,ref.x          |                  |       |
| 4  | 45   | K0       | 6.6  | 3.96      | 3.720  | 0.11     | 1.3           | 6.95              | ext,pm,neb        |                  |           |       |
|    |      | ROXRI-1/SR 8 | 1.6 (2M) | 3.81 | 3.602  | -0.18    | 0.49          | 5.98              | pm,ref.x          |                  |           |       |
| 4  | 17   | M4       | 4.3  | 7.49      | 3.580  | -1.34    | 0.52          | 7.98              | ext,ha,IRX        |                  |           |       |
| 3  | 5    | K6       | 7.8  | 4.92      | 3.621  | -0.35    | 0.70          | 6.51              | ext,ha,IRX        |                  |           |       |
| 3  | 56   | WLY 2-2  | 6.7  | 3.79      | 3.662  | 0.12     | 0.80          | 6.08              | ext,ha,IRX        |                  |           |       |
| 3  | 56   | WLY 2-3  | 3-15 | M2       | 4.8    | 6.42    | 3.544        | -0.90             | 0.32              | 6.58              | ext,ha,IRX        |                  |       |
|    |      | WLY 2-2  | 2-32 | M3.5     | 2.5    | 7.20    | 3.512        | -1.14             | 0.21              | 6.54              | ext,ha,IRX        |                  |       |
| F   | Ap. | Name(s)^a | WMR^b | Sp. Type^c | $A_v$ (mag) | $M_1$ (mag) | log $T_{eff}$ (K) | log $(L/L_\odot)$ | $M_1^r$ (M_\odot) | log(age) (yr) | Criteria^d | Notes^f |
|-----|-----|-----------|-------|-----------|-------------|-------------|----------------|----------------|----------------|--------------|-----------|---------|
| 2   | 32  | M1        | 4.1   | 6.00      | 5.29        | 3.562       | −0.74          | 0.45            | 6.61           | ext,li,x    |          |         |
| 5   | 67  | K8        | 5.5   | 6.09      | 5.914       | −0.79        | 0.71           | 7.15            | ext,li        |              |          |         |
| 1   | 5   | M1         | 3.5   | 4.67      | 3.80        | −0.93        | 0.64           | 7.26            | ext,li,x      |              |          |         |
| 5   | 81  | ISO-Oph 106 | 3-2   | M2.5      | 6.4         | 3.535       | −1.01          | 0.28            | 6.61           | ext,ha,IRX  |          |         |
| 2   | 23  | G1 (MMGC) | 7.6   | (GS)      | 1.12        | 3.774       | 1.29           | 2.9             | 6.26          | ext,IRX,pm,x |          |         |
| 6   | 62  | M3.5      | 4.3   | 7.37      | 3.512       | −1.20        | 0.21           | 6.65            | ext,ha,x      |              |          |         |
| 2   | 35  | M3.5      | 4.9   | 4.72      | 3.591       | −0.24        | 0.46           | 5.99            | ext           |              |          |         |
| 2   | 31  | K5.5      | 5.9   | 4.29      | 3.609       | −0.90        | 0.63           | 6.10            | ext,li,x      |              |          |         |
| 2   | 24  | K5.5      | 3.4   | 4.43      | 3.630       | −0.15        | 0.66           | 6.21            | ext,ha,pm     |              |          |         |
| 1   | 12  | M3.5      | 7.0   | 4.26      | 3.638       | −0.08         | 0.69           | 6.18            | ext,ha,IRX,li,x |          |         |
| 2   | 15  | M4.5      | 1.9   | 7.36      | 3.488       | −1.12         | 0.16           | 6.33            | ext,li,x      |              |          |         |
| 2   | 7   | M4.5      | 2.3   | 9.04      | 3.488       | −0.42         | 0.04           | 7.25            | ext,x         |              |          |         |
| 1   | 9   | WLY 2-48/ISO-Oph 159 | 12 | 1.68 | 3.979 | 1.31 | 2.1 | 7.53 | ext,IRX | | | |
| 2   | 35  | M2.5      | 2.9   | 6.44      | 3.535       | −0.89         | 0.27           | 6.43            | ext,li        |              |          |         |
| 2   | 14  | M3.5      | 2.2   | 7.20      | 3.512       | −1.14         | 0.21           | 6.54            | ext,li,       |              |          |         |
| 2   | 31  | K5.5      | 5.9   | 4.29      | 3.609       | −0.90        | 0.63           | 6.10            | ext,li,x      |              |          |         |
| 2   | 24  | M3.5      | 3.4   | 6.55      | 3.580       | −0.97         | 0.63           | 7.33            | ext,li,x      |              |          |         |
| 2   | 15  | M4.5      | 4.6   | 7.41      | 3.498       | −1.19         | 0.18           | 6.50            | ext,ha,IRX,li,x |          |         |
| 2   | 10  | M3.5      | 1.9   | 7.73      | 3.488       | −1.27         | 0.16           | 6.51            | ext,IRX      |              |          |         |
| 5   | 73  | M0        | 3.4   | 6.55      | 3.580       | −0.97         | 0.63           | 7.33            | ext,li,x      |              |          |         |
| 1   | 24  | ISO-Oph 194 | 4.6   | 7.41      | 3.498       | −1.19         | 0.18           | 6.50            | ext,ha,IRX,li,x |          |         |
| 2   | 12  | M3.5      | 1.9   | 7.73      | 3.488       | −1.27         | 0.16           | 6.51            | ext,IRX      |              |          |         |
| 2   | 25  | M3.5      | 3.4   | 8.05      | 3.512       | −1.48         | 0.22           | 7.07            |   ext         |              |          |         |
| 2   | 16  | M5        | 1.2   | 9.45      | 3.477       | −1.91         | 0.11           | 7.13            |   ha          |              |          |         |
| 2   | 30  | M2        | 4.6   | 6.26      | 3.544       | −0.83         | 0.32           | 6.48            | ext,x         |              |          |         |
| 1   | 26  | M5        | 0.4   | 8.98      | 3.477       | −1.72         | 0.13           | 6.95            |   li          |              |          |         |
| 2   | 44  | M3.5      | 5.3   | 6.68      | 3.512       | −0.93         | 0.20           | 6.27            |   ext         |              |          |         |
| 2   | 45  | M3.5      | 3.2   | 7.28      | 3.512       | −1.17         | 0.21           | 6.59            | ext,ha        |              |          |         |
| 2   | 16  | M4        | 2.8   | 7.25      | 3.498       | −1.13         | 0.18           | 6.41            | ext,li,x      |              |          |         |
| 2   | 7   | M1.5      | 3.9   | 5.61      | 3.553       | −0.58         | 0.35           | 6.20            | ext,ha,li,x   |              |          |         |

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### Notes:

- **Continued**
- **Criteria:**
  - log($T_{eff}$) (K)
  - log($L/L_\odot$)
  - $M_1^r$ (M_\odot)
  - log(age) (yr)
- **Notes:**
  - ext
  - ha
  - IRX
  - pm
  - x
  - var
1989). Star symbols mark the locations of the multiple B star ρ Oph and the three most massive members of the L 1688 embedded cluster: HD 147889, Source 1, and SR 3. While the association members are concentrated toward the molecular gas, there is marked lack of association members in the direction of ρ Oph and the three most massive members of the L 1688 (∼<250 K and underestimate T_{\text{eff}} for stars with spectral types of G5-K5 by ∼<250 K and underestimate T_{\text{eff}} for stars with spectral types of G5-K5 by ∼<250 K and underestimate T_{\text{eff}} for stars with spectral types of M2-M8 by ∼<200 K (e.g., Drilling & Landolt 2000). Intrinsic colors and bolometric corrections for dwarf stars were taken from the works of Schmidt-Kaler (1982) for B8-K5 stars and from Bessell (1991) for K5-M7 stars. For the three B stars, we adopted the intrinsic colors, bolometric magnitudes, and temperatures from Drilling & Landolt (2000), converting the colors into the Kron–Cousins system. For the M8 brown dwarf candidates, we assumed values of T_{\text{eff}} = 2400 K, (R − I)_0 = 2.5, and BC(I) = −1.7 (Dahn et al. 2002; Hawley et al. 2002).

The absolute I magnitude, M(I), was computed given the extinction and assuming a distance of 130 pc. We then derived the bolometric magnitude and luminosity given

\[ M_{\text{bol}} = M(I) + BC(I), \]

where

\[ \log(L_{\text{bol}}/L_\odot) = 1.89 - 0.4M_{\text{bol}}, \quad M_{\text{bol}}(\odot) = 4.74. \]

In the situations where J and H were used to deredden, M(J) is recorded in Column 7 of Table 3 and was used along with BC(J) to derive M_{\text{bol}}. The median error in \log(L) is computed to be 0.14 dex by adding quadratically errors in the R and I photometry, an uncertainty in the distance modulus of 0.17 mag corresponding to a depth of 10 pc, and an uncertainty 0.03 mag in the intrinsic color and 0.1 mag in the bolometric correction due to spectral type errors. In most cases the dominant error was the uncertainty in the distance modulus.

H-R diagrams for 135 association members were made using tracks and isochrones from D’Antona & Mazzitelli (1997, DM), F. D’Antona & I. Mazzitelli (1998, private communication), Pall & Stahler (1999, PS99), and Siess et al. (2000). Despite the differences in treatments of the equation of states as a function of mass and of convection, the models give very similar results for our sample. The diagrams for the former two are shown in

### Notes.

a Sources names from optical or infrared studies noted in Table 2 plus: (SR) Struve & Rudkjøbing 1949; (DoAr) Dolidze & Arakelyan 1959; (EL) Elias 1978; (Chini) Chini 1981; (WL) Wilking & Lada 1983; and (ROXR1) Casanova et al. 1995.

b Source name from Wilking et al. (2005).

c Optical spectral types from this study or Wilking et al. (2005) except where noted: (EL) Elias 1978; (CK) Cohen & Kuihi 1979; (HS) Houk & Smith-Moore 1988; (GS) S. Gordon & K. M. Strom 1990, private communication; (BA) Bouvier & Appenzeller 1992; (TQ) Torres et al. 2006; and (MMGC) Martin et al. 1998.

d R- and I-band magnitudes used to compute A_v and L_{bol} are from this study except where noted: (C) Chini 1981; (GS) S. Gordon & K. M. Strom 1990, private communication; (BA) Bouvier & Appenzeller 1992; and (W) Walter et al. 1994. (2M) denotes 2-to-MASS were used to compute A_v and L_{bol} and M(J) replaces M(I) in Column 7.

References:

- Cohen et al. (1981) in the Kron–Cousins system:
  \[ E = 0.65V \text{mag}, \quad K - \text{mag} \]
  \[ E = 0.65V \text{mag}, \quad K - \text{mag} \]
  \[ E = 0.65V \text{mag}, \quad K - \text{mag} \]

- and

- Hertzsprung–Russell Diagram

To derive luminosities, we began by dereddening sources using the (R − I) color index assuming the reddening law derived by Cohen et al. (1981) in the Kron–Cousins system:

\[ A_v = 4.76E(R - I), \quad \text{Sp Ty < A0 (early-type)} \]

\[ A_v = 6.25E(R - I), \quad \text{Sp Ty > A0 (late-type)} \]

where \( R = 3.2 \) for early-type stars and 3.8 for late-type stars. R- and I-band data were taken from this study except where noted in Column 6 of Table 3. For five sources, R- and I-band data were not available and sources were dereddened using J- and H-band data from the 2MASS survey (Cutri et al. 2003) and transformed into the CIT photometric system using the relationships derived by Carpenter (2001). A sixth source (WL 18) was dereddened using J and H magnitudes since strong Hα emission distorts its R-band magnitude. In these latter cases, we used the relation for the CIT photometric system:

\[ A_v = 9.09E(J - H) \]

In a few instances, the errors in the photometry and/or spectral classifications yielded negative values for the extinction of a few tenths and an extinction of 0.0 was assumed.

Effective temperatures were derived from the spectral classifications with typical uncertainties of ±150 K for K-M stars. We note that the assumption of dwarf, rather than subgiant, surface gravities will overestimate T_{\text{eff}} for stars with spectral types of G5-K5 by ∼<250 K and underestimate T_{\text{eff}} for stars with spectral types of M2-M8 by ∼<200 K (e.g., Drilling & Landolt 2000). Intrinsic colors and bolometric corrections for dwarf stars were taken from the works of Schmidt-Kaler (1982) for B8-K5 stars and from Bessell (1991) for K5–M7 stars. For the three B stars, we adopted the intrinsic colors, bolometric magnitudes, and temperatures from Drilling & Landolt (2000), converting the colors into the Kron–Cousins system. For the M8 brown dwarf candidates, we assumed values of T_{\text{eff}} = 2400 K, (R − I)_0 = 2.5, and BC(I) = −1.7 (Dahn et al. 2002; Hawley et al. 2002).

The absolute I magnitude, M(I), was computed given the extinction and assuming a distance of 130 pc. We then derived the bolometric magnitude and luminosity given

\[ M_{\text{bol}} = M(I) + BC(I), \]

and

\[ \log(L_{\text{bol}}/L_\odot) = 1.89 - 0.4M_{\text{bol}}, \quad M_{\text{bol}}(\odot) = 4.74. \]

In the situations where J and H were used to deredden, M(J) is recorded in Column 7 of Table 3 and was used along with BC(J) to derive M_{\text{bol}}. The median error in \log(L) is computed to be 0.14 dex by adding quadratically errors in the R and I photometry, an uncertainty in the distance modulus of 0.17 mag corresponding to a depth of 10 pc, and an uncertainty 0.03 mag in the intrinsic color and 0.1 mag in the bolometric correction due to spectral type errors. In most cases the dominant error was the uncertainty in the distance modulus.

H-R diagrams for 135 association members were made using tracks and isochrones from D’Antona & Mazzitelli (1997, DM), F. D’Antona & I. Mazzitelli (1998, private communication), Pall & Stahler (1999, PS99), and Siess et al. (2000). Despite the differences in treatments of the equation of states as a function of mass and of convection, the models give very similar results for our sample. The diagrams for the former two are shown in

### Table 3 (Continued)

| F | Ap. | Name(s)a | WMRb | Sp. Typec | A_v^d (mag) | M(I) (mag) | log T_{\text{eff}} (K) | log(L/L_\odot) | M_* (M_\odot) | log(age) (yr) | Criteria^f | Notesg |
|---|-----|----------|------|-----------|------------|-------------|---------------------|----------------|-------------|-------------|----------|--------|
| 5 | 4   | M5.5     | 0.2  | 9.73      | 3.462      | −1.97       | 0.08                | 6.91           | ha,IRX, var|x |          |        |
| 2 | 57  | M5.5     | 0.0  | 8.91      | 3.462      | −1.64       | 0.10                | 6.67           | li          |            |        |
| ROX 35A |      | K3 (BA)  | 2.1 (W) | 3.93 | 3.676 | 0.08 | 1.0 | 6.36 | ext, li, x |            |
| ROX 35B |      | G4 (BA)  | 2.5 (GS) | 3.64 | 3.763 | 0.27 | 1.2 | 7.22 | ext, x |            |
Figure 4. Hertzsprung–Russell diagrams for the ρ Oph association members with optically determined spectral types assuming a distance of 130 pc. The solid diamonds mark the positions of YSOs relative to the theoretical tracks and isochrones of D’Antona & Mazzitelli (1997) and F. D’Antona & I. Mazzitelli (1998, private communication) in (a) or Palla & Stahler (1999) in (b). Error bars in log $T_{\text{eff}}$ were estimated from uncertainties in the spectral type and surface gravity. Error bars in log $L_{\text{bol}}$ were estimated from errors in the photometry and uncertainties in the distance modulus and bolometric correction. In (a), isochrones shown as solid lines are $10^5, 3 \times 10^5, 10^6, 3 \times 10^6, 10^7, \text{and} 10^8$ yr. Evolutionary tracks from 0.02 $M_{\odot}$ to 2.0 $M_{\odot}$ are shown by dashed lines. The bold dashed line marks the evolutionary track for a star at the hydrogen-burning limit. In (b), the birthline is shown as a solid line followed by isochrones for $10^6, 3 \times 10^6, 10^7$, and $10^8$ yr and the ZAMS. Evolutionary tracks from 0.1 $M_{\odot}$ to 6.0 $M_{\odot}$ are shown by dashed lines.
Figure 4 as they represent the broadest range in mass. The masses and ages interpolated from the DM models are given in Table 3. Since most of the objects lie on convective tracks, uncertainties in the mass relative to the DM models were estimated from the errors in the spectral classifications and uncertainties in the age from errors in the luminosities. Uncertainties in the mass for objects in the range of 0.08–1.3 $M_\odot$ were typically 16%–30%, with the higher value corresponding to the lower mass objects. Uncertainties in the log(age) were 0.17–0.25 dex relative to DM models with the greater uncertainty for the higher mass objects. We note that uncertainties in the absolute masses and ages will be larger with theoretical mass tracks underpredicting absolute stellar mass by 30%–50% (Hillenbrand 2009). No age or mass estimate was possible for RXJ 1624.9-2459 as it fell below the $10^3$ yr isochrone.

4.5. Age Distribution

The values for log(age) derived from the DM models are consistent with a normal distribution with an average log(age) of 6.49 ± 0.05 (3.1 Myr). Ages derived from the PS99 models agree surprisingly well while the Siess et al. models yield systematically older ages for log(age) ≤ 7.0; the difference can be as much as 0.4 dex for a DM age of 1 Myr. Given the large areal coverage of our survey (1.3 deg$^2$ or 6.8 pc$^2$), which must include members of the Upper Sco subgroup, an age spread in our sample would not be unexpected. However, simulations do not suggest an intrinsic age spread. Assuming Gaussian-distributed errors in log T and log L and using the DM models for 3 Myr, a Monte Carlo simulation derived values of log T and log L for over 12,000 samples in the mass range of 0.12–1.0 $M_\odot$ weighted by the Chabrier (2003) system mass function. While the simulated age distribution appears somewhat narrower than what we observe, a Kolmogorov–Smirnov (K-S) test cannot reject the null hypothesis that the two samples are drawn from the same parent population at the 3% level. Lack of strong evidence for a large age spread is consistent with what is found in other young clusters or associations (e.g., Hillenbrand 2009; Slesnick et al. 2008) and supports the idea of rapid star formation (Hartmann 2001).

The average age for this sample is somewhat older than the average of 0.3 Myr derived from more obscured sources in the core using the DM models and dereddened using JHK photometry (e.g., Greene & Meyer 1995; Luhman & Rieke 1999; WGM99; Natta et al. 2002). However, we note that there are systematic differences in our derived luminosities, and hence ages, when $(J - H)$ photometry is used to deredden sources instead of $(R - I)$. Using $(J - H)$ colors from 2MASS yields systematically higher values for $A_J$, and hence $L_{bol}$. As a consequence, the average log(age) for our sample dereddened with $(J - H)$ colors is 6.14 ± 0.05 (1.4 Myr) compared to 6.49 ± 0.05 (3.1 Myr) when $(R - I)$ is used. Indeed, a K-S test applied to both versions of our age distributions suggests that the difference is significant. The reason for this discrepancy is not understood but could involve the adopted reddening law (Cohen et al. 1981), surface gravity effects, or possible excess emission in the J and H bands from optically thick disks. J- and H-band excesses will overestimate the luminosity which leads to an underestimate of ages (Cieza et al. 2005). Regardless, the older average age for our sample relative to the more obscured sources is significant when both samples are dereddened using $(J - H)$ (1.3 Myr versus 0.3 Myr) even considering that the previous studies used the pre-Hipparcos distance of 160 pc.

A mid-infrared excess is defined as $\alpha \geq -1.60$ which is characteristic of an optically thick disk (e.g., Greene et al. 1994). This results in 33 of the 123 sources, or 27% ± 5%, showing evidence for a circumstellar disk lacking a large inner hole (see Table 3) with the uncertainty estimated assuming Poisson statistics (Gehrels 1986). We adopt this disk frequency estimated over near- to mid-infrared wavelengths as the most reliable disk indicator. The sample size is not sufficient for investigating possible variations in the disk frequency with spectral type.

As a check, we can use the slope of the 3.6–8.0 $\mu$m flux densities from the Spitzer Space Telescope to assess the fraction of sources with mid-infrared excesses. A linear least-squares fit was made to the flux densities for each source compiled from the Spitzer c2d catalog available in NASA/IPAC Infrared Science Archive. Following Lada et al. (2006), disk models suggest that $\alpha \geq -1.80$ over this wavelength range is indicative of an optically thick disk. The distribution of spectral indices as a function of spectral type is shown in Figure 5. For the 122 sources for which data were available, 40 or 33% ± 5% showed evidence for an optically thick disk consistent with our previous
estimate. We can compare this disk frequency to that derived by Lada et al. for the IC 348 cluster who considered 299 YSOs, most of which reside in an area completely sampled for $M > 0.3 \, M_\odot$ and $A_v < 4$ mag (Luhman et al. 2003). Their value of 30% ± 4% for IC 348 is consistent with our disk frequency which is not surprising given the similarity in the cluster’s estimated age of 2–3 Myr (Herbst 2008).

With knowledge of the spectral types, we can also look for evidence of even smaller infrared excesses from the inner disk in the $K$ band. Using data from the 2MASS survey, we transformed the magnitudes into the CIT system and dereddened them using Equation (3). Assuming that the excess at $J$ was zero, the difference of the dereddened $(J-H)$ color to the intrinsic color was then used to estimate

$$r_H = F_{H\kappa}/F_H,$$

where $F_{H\kappa}$ is the broadband flux from circumstellar emission and $F_H$ is the expected stellar flux at 1.6 $\mu$m. This was then used to estimate the excess at $K$:

$$r_K = F_{K\kappa}/F_K = (1 + r_H)(10^{[(H-K)-(H-K)_{\text{0}}-0.065A_v]/2.5} - 1).$$

Values of $\Delta K = \log(1 + r_K)$ were computed and those that equaled or exceeded 0.20 were associated with an optically thick inner disk (Skrutskie et al. 1990). We note that three sources with an apparent $K$-band excess did not display a mid-infrared excess; all three have values close to $\Delta K = 0.20$ and may be identified as excess sources due to photometric errors. Twenty-three of 123 sources, or 19% ± 4%, showed evidence for an optically thick inner disk. While the assumption of no excess emission at $J$ could underestimate $\Delta K$, the higher percentage of mid-infrared excess sources is typical of young clusters and likely reflects the greater sensitivity of mid-infrared photometry to disk emission (e.g., Meyer et al. 1997; Haisch et al. 2000).

The dispersal of the inner disk by accretion, stellar winds, and/or planet formation could also contribute to the lower disk frequency derived from the $K$ band. Candidate transition disk objects with a mid-infrared excess and $\Delta K \leq 0.10$ include WSB 18, ISO-Oph 1, WSB 52, ISO-Oph 195, and Object 2-57, SR 21, DoAr 25, SR 9, and WMR 2-37. The latter four have been confirmed as transition disk objects through modeling of their spectral energy distributions from optical through millimeter wavelengths (Eisner et al. 2009; Cieza et al. 2010; Andrews et al. 2011).

4.6.2. Initial Mass Function

Previous investigations of the IMF in $\rho$ Ophiuchi have produced diverse results. Luhman & Rieke (1999) used $K$-band spectra for approximately 100 stars; mass estimates for 36 plus completeness corrections were used to construct an IMF. Their IMF is roughly flat from 0.05 to 1 $M_\odot$ and peaks at ~0.4 $M_\odot$. de Marchi et al. (2010) use these data and fit it to a tapered power law, and derive a characteristic mass of 0.17 $M_\odot$. Marsh et al. (2010) also derive an IMF for $\rho$ Ophiuchi which continues to rise into the brown dwarf regime, however this study was completely photometric in nature.

We divided the 123 YSOs that formed an extinction-limited sample ($A_v \leq 8$ mag) into mass bins with a width in log(mass) of 0.4 dex. No correction was made for close binaries. A plot of the resulting mass function, shown in Figure 6, displays a peaks and turns over at 0.13 $M_\odot$. The last three mass bins are not complete for $A_v = 8$ mag, so completeness corrections were made assuming an age of 3 Myr. To this end, the maximum visual extinction to which a source could be observed, $A_{\text{max}}$, was estimated for a source in the center of each mass bin using the DM models and assuming an $I$-band limiting magnitude of 15.9. This value, estimated from Figure 2, is where the 3 Myr isochrone intersects our completeness limit. To account for variations in extinction within the region, we used the extinction maps from Ridge et al. (2006) with an effective resolution of 3'. The fractional area of our survey box with $A_v = 0–2$, 2–4, 4–6, 6–8, and $>8$ mag was estimated to be 0.09, 0.32, 0.24, 0.14, and 0.21, respectively. We then estimated the number of missing sources for each extinction interval assuming a uniform stellar surface density weighted by the fractional area. For the three lowest mass bins, the number of sources would increase by a factor of 1.04, 1.43, and 3.32. While our completeness corrections are dependent on the choice of PMS model and reddening law, the use of other models instead of DM does not significantly change these corrections.

For comparison with our IMF, the lognormal system mass function derived by Chabrier (2003) for field stars with $M \leq 1.0 \, M_\odot$ is shown in Figure 6 integrated over our mass bins and normalized to the observed number of objects in the 0.08–0.20 $M_\odot$ mass bin. For $M > 1.0 \, M_\odot$, a power law of the form $\xi(\log m) \propto m^{-1.3}$ was used. Error bars plotted in Figure 6 were calculated using the methods of Gehrels (1986) and multiplied by our completeness corrections. In order to make an overall (large scale) comparison of the IMF with other regions and the field star IMF, we computed the ratio of high (1–10 $M_\odot$) to low (0.1–1 $M_\odot$) mass stars. For our sources, this ratio is $R = 0.12$ and 0.10 when including our completeness corrections with an uncertainty of ±0.04 calculated using the methods of Gehrels (1986). Our value of $R$ is in agreement with values found for $\rho$ Ophiuchi and other young embedded clusters (Meyer et al. 2010) for fields stars with $M \leq 1.0 \, M_\odot$.
The ratio of high-to-low-mass stars for a Chabrier system IMF is 0.16, hence we conclude that coarsely our mass function is consistent with that of the field star IMF. To make a more detailed comparison, a K-S test was performed over the mass ranges for which no completeness corrections were necessary \((M > 0.2 M_\odot)\). We cannot reject the null hypothesis that the samples were drawn from the same parent population with a probability of 40%, suggesting that the IMF of \(\rho\) Ophiuchi is not significantly different from the field star IMF over this mass range.

When examined in more detail, there might be subtle differences between our mass function and the field star IMF. Chabrier’s (2003) lognormal IMF underestimates the number probability of 40%, suggesting that the IMF of samples were drawn from the same parent population with a probability of 40%, suggesting that the IMF of \(\rho\) Ophiuchi is not significantly different from the field star IMF over this mass range.

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Our peak mass of 0.13 \(M_\odot\) is consistent with that of the field star IMF. To make a more detailed comparison, a K-S test was performed over the mass ranges for which no completeness corrections were necessary \((0.08 \leq M \leq 1\) \(M_\odot\)). We cannot reject the null hypothesis that the samples were drawn from the same parent population with a probability of 40%, suggesting that the IMF of \(\rho\) Ophiuchi is not significantly different from the field star IMF over this mass range.

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**5. TEMPORAL RELATIONSHIP WITH UPPER Sco**

Given the larger data set for YSOs distributed in the low-extinction regions of the L 1688 cloud, we revisited the relationship between star formation in this extended region \((6.8 \text{ pc}^2)\) to that in the L 1688 cloud core and in the Upper Scorpius subgroup of the Sco-Cen OB association. As noted in Paper I and Section 4.5, spectroscopic studies of embedded sources in the 1 pc \times 2 pc centrally condensed core have consistently yielded ages between 0.1 and 1 Myr when using the D’Antona & Mazzitelli tracks and isochrones, with a median age of 0.3 Myr. The median age for the distributed population is significantly older than that in the higher extinction cloud core.

In Paper I we compared our H-R diagram for 88 association members in L 1688 with that of the 252 members of the Upper Scorpius subgroup compiled by Preibisch et al. (2002) and noted there were no significant differences in age between the two samples. However, comparisons with the Upper Scorpius sample are more complicated since Preibisch et al. derived temperatures and luminosities in a different manner. For example, \(R\) - and \(I\)-band photometry was obtained from the UKST Schmidt plates, intrinsic colors from Hartigan et al. (1994), and the reddening law from Herbig (1998) plus a combination of evolutionary models were used (but primarily those of Palla & Stahler 1999). To ease the comparison between the two samples, we compiled \((J−H)\) photometry for sources in both samples from the 2MASS catalog (Cutri et al. 2003), transformed it to the CIT system, and derived extinctions and luminosities as described in Section 4.4. A dwarf temperature scale was used to relate spectral types in both samples to effective temperatures. We note that a distance of 130 pc was used for L 1688 and 145 pc for Upper Sco (de Zeeuw et al. 1999). The H-R diagram for the Upper Sco sample is shown in Figure 7 relative to the theoretical tracks and isochrones from D’Antona & Mazzitelli. Ages were interpolated for sources in both samples using the DM models. The average log(age) for the Upper Sco sample is 6.43 (2.7 Myr) compared to 6.14 (1.4 Myr) for L 1688. A K-S test applied to both samples suggests that they are not drawn from the same parent population. Hence, in this reanalysis, the low-mass objects distributed across the L 1688 cloud appear intermediate in age between low-mass stars in Upper Sco and YSOs embedded in the centrally condensed core. Consistent with this picture is the lower fraction of K0–M5 stars in Upper Sco with optically thick disks (19%; Carpenter et al. 2006) compared to ~30% from this study.

Do the timescales involved allow the formation of the distributed population of L 1688 to be triggered by events in Upper Sco?
Sco? If a supernova helped power an expanding H\textsc{i} shell originating in Upper Sco and moving at \(\sim 15\ \text{km}\ s^{-1}\) as proposed by de Geus (1992), then in 1 Myr it would move about 15 pc and barely cover the distance in the plane of the sky between the center of Upper Sco and L 1688. A triggering event from Upper Sco would be consistent with the average age difference of \(\sim 1.3\ \text{Myr}\) between low-mass stars in Upper Sco and L 1688. By retracing the motions of high proper motion objects, Hoogerwerf et al. (2001) suggest that a supernova in a binary system occurred in Upper Sco about 1 Myr ago that produced the runaway star \(\xi\) Oph and the pulsar PSR J1932+1059. But this would have been too recent for a shock wave to cross the 15 pc expanse between the two regions and initiate the formation of low-mass YSOs in L 1688 with an average age of 2–3 Myr, thus requiring an earlier event.

6. SUMMARY

Over 200 moderate resolution optical spectra were obtained for candidate YSOs in a 1.3 deg\(^2\) area centered on L 1688. When combined with the 136 spectra obtained in our initial spectroscopic study in Paper I, 135 objects with optical spectral types are now identified as association members based on the presence of H\textalpha\ in emission, X-ray emission, lithium absorption, a mid-infrared excess, a common proper motion, reflection nebulousity, or extinction considerations. Fifteen of these display H\textalpha\ in emission consistent with being newly identified CTTS.

Masses and ages were derived for association members using several theoretical models. Using the tracks and isochrones from D’Antona & Mazzitelli (1997) and F. D’Antona & I. Mazzitelli (1998, private communication), we derive an average age of 3.1 Myr for this distributed population. We find a circumstellar disk frequency of 27\% for this surface population and a characteristic mass of \(123\ \text{YSOs}\ (\pm 5\%)\) for our sample, consistent with our derived age and results from other studies.

The age of 3.1 Myr for this surface population is intermediate between that of YSOs embedded in the cloud core of \(\rho\) Ophiuchi and low-mass stars in Upper Sco.

We also constructed an IMF for an extinction-limited sample of 123 YSOs \((A_v < 8\ \text{mag})\), which is a significant increase in sample size and mass range over previous studies. The resulting IMF is consistent with the field star IMF for YSOs with mass > 0.2 \(M_\odot\). However, it may be inconsistent for masses below 0.2 \(M_\odot\). We find that our sample has a lower characteristic mass \((\sim 0.13\ M_\odot)\) than the field star IMF as well as a possible deficit of brown dwarfs.

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APPENDIX

PHOTOMETRY REVISED FROM PAPER I

A reanalysis of the \(R\)- and \(I\)-band photometry presented in Table 2 of Paper I necessitated some revisions. These revisions, presented in Table 4, are due in large part because of saturation problems with some of thebrighter association members. In these cases, photometry was adopted from other studies as noted.

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