Proceedings of 12th Cambridge Workshop on Cool Stars, Stellar Systems, & The Sun, 2003 University of Colorado.

Very Low-Mass Stars and Candidate Brown Dwarfs in the Orion OB1b Sub-Association

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Abstract.
We are conducting a large scale, multiwavelength survey of 5 sq. degrees of the Orion OB1b sub-association (Walter et al. 2000), a 2Myr old fossil OB association 440pc from the Sun. Young fossil OB associations are especially good sites to study the very low-mass end of the initial mass function (IMF) because low-mass stars and brown dwarfs are brightest during their pre-main-sequence (PMS) phase and brown dwarfs are still relatively hot. We identify candidate PMS stars by their position in the PMS locus of the color magnitude diagram traced by X-ray selected PMS stars. Our results for the first 2 sq. degrees of the association identify about 800 candidate PMS stars per sq. degree. Roughly 40% are in fact members of the association. We estimate masses by comparing PMS models with our BVRI photometry and with 2MASS JHK photometry. We have found 23 objects that are well fit by brown dwarf models.

1. Introduction

OB associations are the typical natal environment of low-mass stars. Early work on low-mass star formation concentrated on T association where a low-mass star may form in relative isolation undisturbed by its distant, relatively quiet neighbors. This quiet environment has been the normal backdrop for theoretical scenarios of low-mass star formation. An OB association is a very different environment from a T association. High mass O and B stars have strong winds and high UV luminosities which remove gas from their vicinity. Stars form in a crowded environment, possibly competing with each other for gas. The crowding and proximity of the low-mass stars to the O stars of the OB association may promote the formation of very low-mass stars and brown dwarfs. Luhman (2000) found significantly fewer brown dwarfs in the Taurus T association than would be expected based on observations of OB associations. Observations of the Orion OB1 association find a large population of very low-mass stars and brown dwarfs in the Orion Nebular Cluster and around σ Ori (See Béjar these proceedings). In fact, the mass function in OB association may extend down to less than $10M_J$ (Béjar et al 2001).

We are conducting a large scale, multiwavelength survey of the Orion OB1b sub-association (Walter et al. 2000), a young fossil OB association 440pc from

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the sun with an age of ∼2Myrs (Brown et al. 2002). Young fossil OB associations are especially good sites to study the very low-mass end of the IMF because low-mass stars are brightest during their PMS phase and very young brown dwarfs are relatively hot and bright. These regions are largely free of bright emission and obscuring dust which complicate the analysis and interpretation of younger regions of active star formation.

We are particularly interested in the very low-mass end of the IMF because many models of star formation indicate that it is more sensitive to the physical conditions which regulate star formation.

2. Observations and Data Reduction

We observed ∼2 deg^2 of the Orion OB1b sub-association with the CTIO 0.9m in 1997 and 1998. For each of our 1997 fields we took 90 and 15 second BVRI images. In 1998 each field was observed at BVRI with longer 300s exposures to reach down to the brown dwarf limit and with 10-20s exposures to avoid saturating the brighter stars. We used 300s VRI exposures for our control fields. Here we report on results from ∼1.5 deg^2 of these data.

Photometry was done with the IRAF[1] version of DAOPHOT for the 1997 fields and with the IRAF APPHOT routine for the 1998 data. Our data are complete to V∼19 (0.11$M_\odot$ for D=440pc and τ=2Myrs), but many of our fields are deeper. For astrometric positions we use D. Mink's IMWCS program (1997) with USNO-A2.0 (Monet 1996) astrometric standards to determine the positions of stars from our optical data. Our positions are accurate to ∼0.1".

We matched our PMS stars with sources from the second incremental release of the 2MASS survey to get our JHK magnitudes.

2.1. Selection of Candidate PMS Stars

Wolk (1996) showed that X-ray selected weak T Tauri stars near σ Ori trace a clear PMS locus which lies below the birthline and above the main sequence in the optical color-magnitude diagram (CMD). We use this PMS locus to select PMS stars in other regions of the OB1b sub-association.

Figure 1 shows the CMD for 11,500 stars near δ and ϵ Orionis. We select ∼1300 of these as candidate PMS stars (with ∼700 above the completeness limit).

About 900 of our candidate PMS stars were detected by 2MASS. We concentrate on these stars for mass determination. These stars have estimated luminosities which are less uncertain because we have photometric data which cover the region of the spectrum where low-mass stars emit most of their energy. With JHK data, we can better estimate the reddenning. As may be seen in left panel of figure 3, Reddening is generally quite low, less than A_v ∼0.5. This is important because reddening makes stars mimic lower mass stars.

[1]IRAF is the Image Reduction and Analysis Facility. It is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

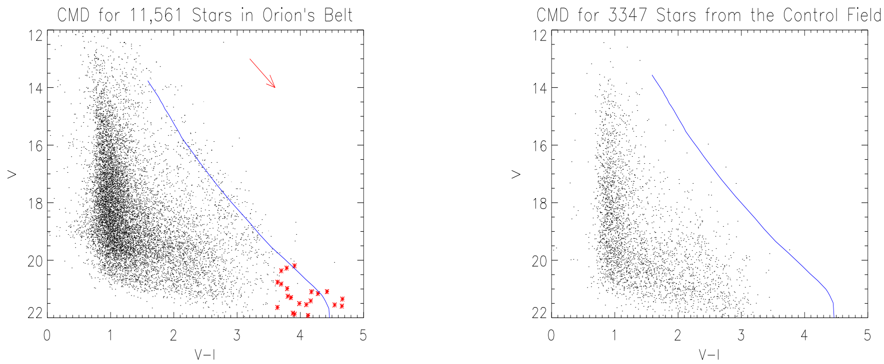

Figure 1. **Left:** This is the V-I vs V CMD for 11,500 stars near ϵ and δ Orionis. The line is a 3 Myr isochrone (Baraffe et al. 1998) plotted with the intermediate temperature scale suggested by Luhman (1999) and colors from Kenyon & Hartmann (1995). We assume a distance of 440pc (Brown et al. 2002). The red stars mark candidate brown dwarfs. **Right:** The V-I vs V CMD for 3347 stars in our control field. The line is also a 3 Myr isochrone. In contrast to our fields near ϵ and δ Ori, there are very few stars near the isochrone.

3. Estimating Masses from PMS Tracks

We first convert observed VRIJHK magnitudes into fluxes. This allows us to plot the spectral energy distribution and check for an infrared excess which would indicate significant emission from a circumstellar disk. Few of the stars we observed seem to have significant near IR excesses.

To estimate masses, we compare our photometry to model PMS stars. Since we are interested in very low-mass stars, we have selected the models of Baraffe et al. (1998). We chose these models because they are consistent with observations of PMS stars in multiple systems. These models are able to match the luminosity and temperature of the PMS components of multiple systems with models that have coeval ages (Simon et al. 2001).

For each model we calculate χ^2 by comparing the observed VRIJHK fluxes to the predicted VRIJHK fluxes. We then fit χ^2 as a function of mass and calculate the mass with the minimum χ^2. We then interpolate to make a model with the estimated mass.

3.1. Mass Function and Brown Dwarf Candidates

Roughly 600 of our candidate PMS stars are well fit by a 2 to 6 Myr old PMS star at an assumed distance modulus of 8.2 mag. Those which are not well fit are either field stars or PMS stars with $M>1M_\odot$ which is the highest mass model.

Figure 3 is the *preliminary* mass function of our candidate PMS stars. Up to our completeness limit of V=19, the mass function has a slope ($\frac{dLog(N)}{dLog(M)}$) of -0.6±0.1 which is consistent with a flattening of the mass function for the mass range $0.1M_\odot < M < 1M_\odot$. We consider this a very preliminary finding because our sample of candidate PMS stars includes field stars which happen to lie on

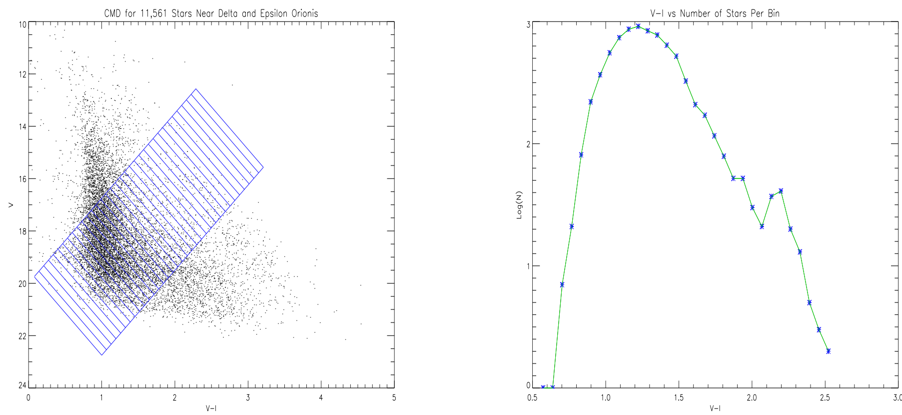

Figure 2. **Left:** This is the same CMD as the left panel of figure 1. The blue boxes are bins which we have used to count the number of stars as a function of distance away from the PMS locus. **Right:** This plot shows the number of stars as a function of position in the CMD. The abscissa is the V-I position of the center of the bin. The ordinate is the number of stars in each bin. The PMS locus stands out clearly.

the PMS locus. We have used figure 2 to estimate the relative number of PMS stars and field stars. In the region marked by the blue bins, we find that the PMS locus stands out clearly. To estimate the fraction of stars in the PMS locus which are field stars, we fit the number of field stars in each bin. We find that for $M{\sim}0.3M_{\odot}$ about 60% of the stars are PMS stars. The fraction of PMS stars is less for both higher-mass and lower-mass stars. We estimate that the overall fraction of PMS stars is ∼40%. The large number of field stars in our sample adds significant uncertainty to our mass function. We are continuing to work to better model the field star distribution so we may reduce the number of field stars in our sample.

Twenty-three of our objects are consistent with the brown dwarf models from Baraffe et al. 1998. These objects are the red stars in figure 1.

4. Discussion

4.1. Uncertainties in Masses from PMS Tracks

It is important to remember that our derived masses are model dependent. Fortunately, recent PMS models are consistent with the few dynamical masses which have been measured for PMS binary systems (Simon et al. 2001).

Very low-mass PMS stars have cool atmospheres which are dominated by molecular lines. The opacity from molecular lines alters the effective temperature of PMS models and the observed colors. This makes it important to include a realistic model atmosphere when calculating PMS models. The Baraffe (1998) models have been calculated with realistic model atmospheres.

The choice of a temperature-color relation is crucial in estimating PMS masses since models predict a star's surface temperature but we observe its

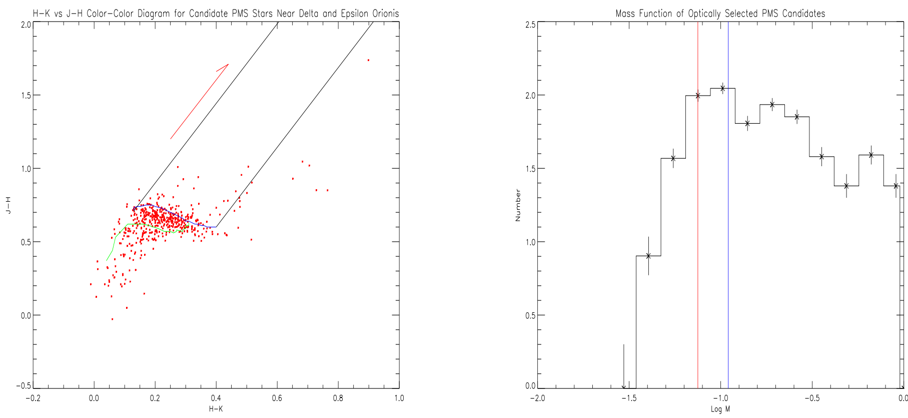

Figure 3. **Left:** A color-color diagram of PMS candidates which have 2MASS photometry. The red arrow illustrates an A_v of 5. Only a few of the candidate PMS stars have A_v much greater than 0.5. **Right:** The mass function calculated from our data. The blue line is our completeness limit. The red line is the sub-stellar limit. The number of stars does not drop steeply after our completeness limit because a few of our fields are deeper than the survey as a whole.

color. This is a particularly difficult step for very low-mass objects because of the many molecular bands in the latest type spectra and because a star's surface gravity changes the temperature-color relationship. PMS stars are larger than main-sequence stars but smaller than giants, so they should have a temperature-color relation that is intermediate between dwarfs and giants. The uncertainty in the temperature-color relation for PMS stars is a major source of uncertainty in the estimated masses. The model atmosphere colors included with the (Baraffe et al. 1998) are a poor match to the apparent locus of PMS stars in the V-I vs V CMD. Colors as given by Kenyon & Hartmann (1995) with Luhman's temperature scale closely follow the apparent locus of PMS stars.

Another major uncertainty in mass estimates for candidate brown dwarfs arises from the fact that they are so cool that they are off of the Luhman temperature scale. For brown dwarfs we have only magnitudes predicted by the model atmospheres of the Baraffe et al. (1998) models, or empirical colors of dwarfs. The optical magnitudes predicted by the model atmospheres differ from those of Luhman's temperature scale, especially for the V band. When we fit our brown dwarf candidates with Baraffe's tracks using Luhman's temperature scale, most of our brown dwarf candidates are well fit by models of very low-mass stars (0.08 to 0.11 $M_\odot$).

The masses also depend on the assumed distance modulus to the Orion OB1b sub-association. We have used 8.2 for the distance modulus (440 pc) to the OB1b sub-association. A smaller distance modulus requires less luminous models to fit the observed data. If a distance modulus of 7.8 is assumed, then our brown dwarf candidates are fit by models which are about 0.005 to 0.01 $M_\odot$ less massive and about a few Myrs older. In most cases, this is within the 1σ error contours of our mass estimates.

5. Summary

We identified ~1300 candidate PMS stars (700 brighter than V=19.0) in a 1.5 deg^2 region of the Orion OB1b sub-association. We expect roughly 40% are in fact PMS stars. We expect that the contamination by field stars is greatest at larger masses because the mass function predicts many more low-mass stars.

We identified 23 candidate brown dwarfs with masses between 0.04 and $0.075M_\odot$ in the ~1.5 deg^2 area of these data or about 15 per deg^2.

The main uncertainty in the masses of our candidate brown dwarfs is the choice of color-temperature relation. Baraffe et al. (1998) include model atmospheres in their PMS models which they also use to generate colors. Luhman (2000) suggested a temperature-color relation intermediate between main sequence and giant stars. Data which are well fit by the Baraffe et al. brown dwarf models (with the Baraffe et al. colors) appear to be very low-mass stars when the Luhman temperature-color relation is adopted.

Acknowledgments. We are grateful to the University of Colorado, CASA, and NASA for financial support.

References

Bahcall, J. N. & Soniera, R. M. 1980, ApJS44, 73

Béjar, V. J. S., Zapatero Osorio, M. R., & Rebolo, R. 1999 ApJ521, 671

Baraffe, I., Chabrier,G., Allard,F., & Hauschildt,P. 1998 A&A, 337, 403

Béjar, V. J. S., et al. 2001 ApJ521, 671

Brown, A. G. A., Walter, F. M., & Blaauw, A. 2002 in ASP Conf. Ser., *The Orion Complex Revisited* ed. M. J. McCaughrean & A. Burkert, in press

Hillenbrand, L. & Carpenter, J. 2000 ApJ556, 830

Kenyon, S. J. & Hartmann, L. 1995 ApJS101, 117

Luhman, K., 1999 ApJ525, 466

Luhman, K., 2000 ApJ544, 1044

Mamon, G. A., & Soneira, R. M. 1982, ApJ255, 181

Mink, D. J., 1997, in *Astronomical Data Analysis Software and Systems VI*, A.S.P. Conference Series, Vol. 125, G. Hunt and H. E. Payne, eds., p. 249

Monet,D. et al. 1996, USNO-A1.0, (U.S. Naval Observatory, Washington DC)

Palla, F., Stahler, S. W. 1999, ApJ 392, 667

Padoan, P., & Nordlund,Åastro-ph/0011465 (submitted to /apj)

Simon, M., Dutrey, A., & Guilloteau, S. 2001 ApJ 535, 1034

Walter, F. M., Alcalá, J. M., Neuhäuser, R., Sterzik, M., & Wolk, S. J. 2000, in *Protostars and Planets IV*, V. Mannings, A. P. Boss, and S. S. Russell

Walter, F.M., Wolk, S.J., & Sherry, W.H., 1998, in *Cool Stars, Stellar Systems, and the Sun 10*, R Donahue & J. Bookbinder (ASP: San Francisco)

Wolk, S. J. 1996 *Watching the Stars go 'Round and 'Round*, PhD Thesis, State University of New York, Stony Brook