Very Low Mass Objects in Orion OB1a and b

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Abstract. We present initial results of a search for the substellar mass population of the Orion OB1 a and b associations, based on a deep optical/near-IR survey. We are complete to about 1 magnitude fainter than the 2MASS survey at K. Global comparison of the K vs. $J-K$ color-magnitude diagram shows an excess of objects with $K>$14.4 (the substellar limit in Orion OB1b) and $0.8 < J-K < 1.0$. The $BVRIJHK$ spectral energy distributions are consistent with unreddened 2 Myr old substellar mass objects at the distance of Orion OB1b. Near-IR spectra confirm spectral types near M7, and show the triangular H-band continuum shape associated with young (low gravity) objects. Space densities of these objects exceed a few hundred/deg^2 near δ Orionis.

Keywords: Stars: formation; Stars: low mass, brown dwarfs
PACS: 95.75.Fg, 95.85.Jq, 95.85.Kr, 97.10.Bz, 97.21.+a, 98.20.Af

MOTIVATION

There is evidence that the densities of substellar mass objects (SSMOs) are higher in OB associations than in the field. Why? Do OB winds and UV fluxes evaporate small cores? Are underdone embryos ejected prematurely? To examine, and possibly answer, these questions, we are observing Orion OB1, the largest nearby OB association and fossil star formation region (FSFR).

In FSFRs:

- The dust and gas are largely dispersed, a consequence of the OB star radiation fields, winds, and the occasional supernova. Extinction is generally small. Useful observations can be made at many wavelengths, not just at longer wavelengths.
- All the stars are visible and are distinct from the field. Members are still spatially concentrated, and can be identified from radial velocities, proper motions, or by spectroscopic indicators of youth.
- Few stars retain optically thick circumstellar disks. Colors are photospheric.
- Accretion is over: all objects have attained their final masses. There is little chance that an SSMO will accrete enough mass to become a star.
- The stars are nearly coeval. Differences in absolute ages of order 1 Myr are of much less consequence at 10 Myr than at 1 Myr.
- Stellar evolution models have converged, irrespective of the initial conditions chosen. At ages of <1Myr, as in many embedded star forming regions, evolutionary models are unreliable, because the predicted observables are dependent upon the initial conditions imposed by the modeler.

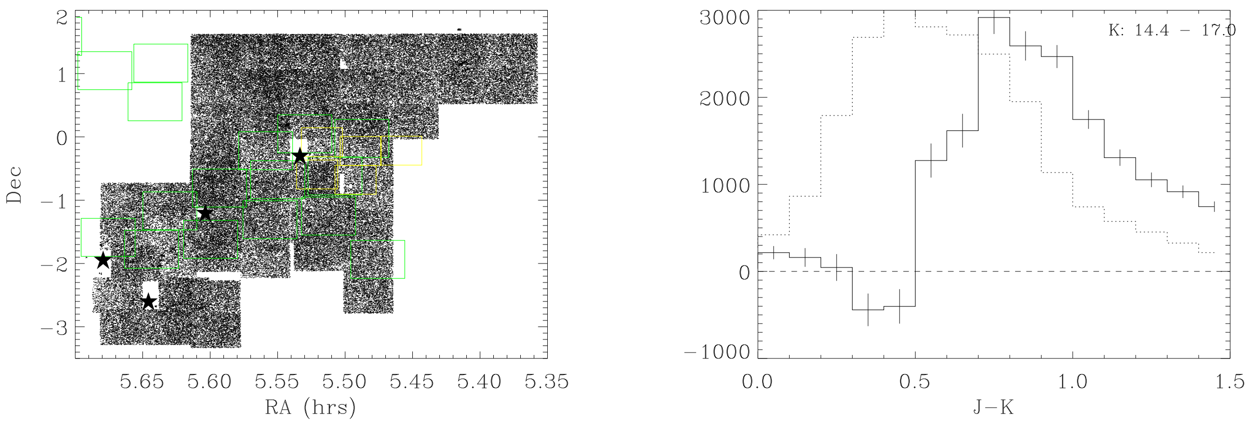

FIGURE 1. Left: All 146,905 CPAPIR sources in the Orion region (the unresolved dots). Big stars are δ, ε, ζ, and σ Ori. The green boxes outline the completed deep 4m MOSAIC VRI fields; yellow boxes are the 5 completed NEWFIRM fields. Right: The excess in the CMD in the substellar mass regime for $14.4 < K < 17.0$ (solid line). The dotted line is the scaled CMD for the comparison fields, which has been subtracted. There is evidence for some reddening of background sources.

- SSMOs are still warm and luminous. Between 2 and 10 Myr, the absolute *K* mag of a 25 Jovian mass object fades from *K*=8 to *K*=8.5; it fades another 3 mags by 100 Myr. Even at the distance of Orion OB1, planetary mass objects are detectable with modest sized telescopes.

Sherry et al. (2004) showed that the low mass stars near σ Ori trace a field star mass function. Walter et al. (2003) and Faherty et al. (2006) showed there exist a substantial number of fainter objects with colors consistent with 1-20 Myr old substellar mass objects. There have been a number of deep investigations in selected areas of the OB association, especially in the σ Ori cluster. Downes et al. (2008) have recently published a large scale *IJHK* survey of Ori OB1a and b to below the substellar mass limit.

This deeper survey of Orion OB1b (the belt) and parts of Orion OB1a and c is intended to trace the mass function deep into the substellar regime. We seek to determine how very low mass stars and sub-stellar mass objects form in OB associations.

THE DATA

We obtained *JHK* images using the CPAPIR imager on the SMARTS/CTIO 1.5m telescope between October 2006 and January 2008. The CPAPIR images a 35' field of view. The images were astrometrically and photometrically calibrated against 2MASS stars in the field. We extrapolated to fainter magnitudes assuming a linear response. The median completeness of [16.35, 16.35, 15.55] mag, respectively, in [*J*, *H*, *K*] corresponds to a $0.02M_\odot$ mass member of Orion OB1a or b. The completeness in individual fields varies by up to -0.4/+1.6 mag depending on conditions. We go deeper than the 2MASS completeness by [0.2, 0.9, 0.9] mag at [*J*, *H*, *K*]. We have observed

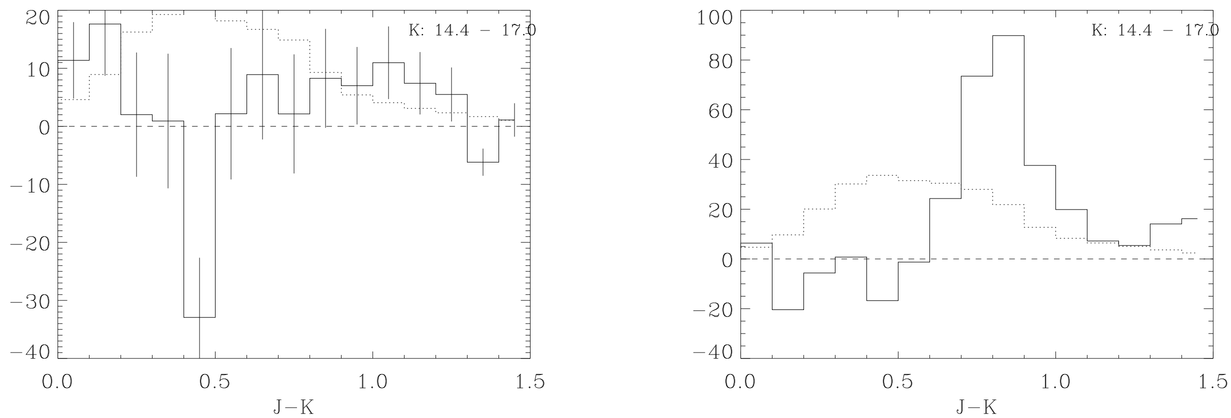

FIGURE 2. Left: The excess objects in the CMD of a field NE of Orion's belt. There is no significant excess. Right: The excess SSMO counts in a 0.34 deg^2 region 2 deg north of δ Ori. The 228 excess objects suggest a space density of over 670 SSMOs/deg^2. In both plots the dotted histogram is the shape of the comparison field CMD, scaled in amplitude.

54 fields (146905 stars; see Figure 1L) in Orion at *JHK*. Another 21 fields have been observed only in *J* and *H*. In addition, we observed 7 comparison fields (37046 stars) at the galactic latitude of Orion.

We have obtained new deep optical imaging of the area. Using the Steward Bok 90-prime camera, we have now imaged 75% of OB1b in *VRI* to V=22 and I=20. With MOSAIC on the Mayall 4m, we have imaged 17 fields in OB1a and b in *VRI* to V=26 and I=24. We have also obtained some deeper near-IR data using the NEWFIRM imager on the Mayall 4m. To date we have observed five 0.4 deg fields near δ Ori in *JHK* to J=19.5 and K=18. Data reductions are still incomplete. When done, we expect our magnitude limits to translate into a completeness level well below 0.01 $M_\odot$, which is in the superplanet regime, over most of OB1b and parts of OB1a and c.

We identify possible SSMOs by excess density in the CMD. We scale (at $J-K<0.5$) and subtract the CMD of the comparison fields. An excess at $0.8<J-K<1.0$ and $K>14.4$ is indicative of SSMOs (Figure 1R). We can estimate the space density of SSMOs from this excess; it ranges from insignificant (Figure 2L) northwest of the belt to close to 1000/deg^2 in some regions (Figure 2R). This type of statistical analysis is fraught with uncertainties. We implicitly assume negligible reddening and IR excesses. This is demonstrably incorrect in some regions with large excess of very red ($J-K>1.2$) objects.

We generate spectral energy distributions (SEDs; see Figure 3L) from the photometry. While these in principle yield the masses and ages, they are not unique because the parameters we fit are not independent. For example, age and distance are degenerate, and mass and luminosity are related at a given age. Young objects in this mass range evolve more-or-less vertically down the CMD. A younger or more massive SSMO will be more luminous and hence appear as bright as an older, closer SSMO.

Spectra can be used as another handle on the stellar youth. Young SSMOs have

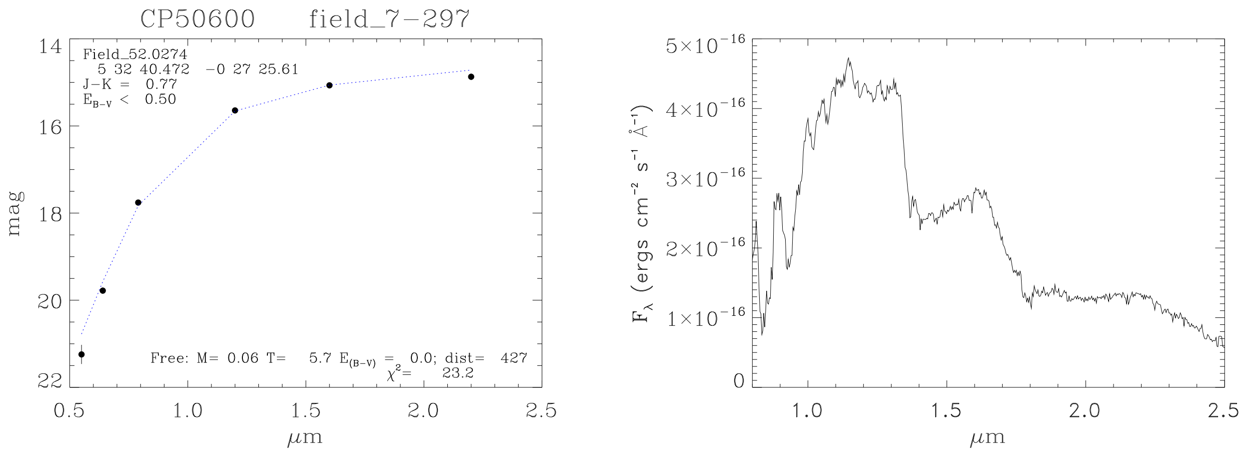

FIGURE 3. Left: An SED best fit with a 0.06 $M_\odot$ SSMO at a distance of 430 pc, consistent with membership in Ori OB1b. Right: The SpeX prism spectrum of one of our low mass SSMO candidates. The spectral type is M7. K=14.6, making this an SSMO at the distance and age of Orion OB1.

spectral types of M5-M7, at least in the mass range we can reach. Young SSMOs have a distinctive triangular-shaped continuum in the H-band (Kirkpatrick et al. 2006; Allers et al. 2007). We obtained spectra of 19 candidate SSMOs using the IRTF/SPEX. Fourteen of the targets are spectral type M5-M7, and most do indeed show the distinctive H-band continuum (Figure 3R).

CONCLUSIONS

Our CPAPIR survey finds about 10,000 SSMOs ($K > 14.4$; $0.8 < J-K < 1.2$) among 146,000 objects in $\sim$13 deg^2 of Orion OB1b. SEDs in the $VRIJHK$ bands are consistent with SSMO membership in Ori OB1, but we are limited by the depth of the optical data to objects just below the substellar mass limit. Deep optical photometry, in progress, will let us reach into the superplanet regime Deep NEWFIRM observations in selected regions will let us probe another 1-2 magnitudes deeper in the near-IR. Our goal, to map the spatial distribution of the SSMOs in this OB association, will provide insights into the formation and dispersion mechanisms of the very low mass objects in OB associations.

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