THE LUMINOSITY FUNCTION OF ULTRACOOL DWARFS

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Abstract

We have created a statistically complete sample of M7–L8 dwarfs within 20 pc using the Two Micron All-Sky Survey (2MASS) Second Data Release. Using this dataset, we present the first robust measurement of the luminosity function of objects that span the stellar/brown dwarf boundary. In addition, we have doubled the number of ultracool dwarfs known within 20 pc. We describe these results and discuss the implications on the mass function.

Key words: Galaxy: stellar content — solar neighborhood — stars: late-type stars: low-mass, brown dwarfs — stars: luminosity function

1. Introduction

The Galactic Disk contains a great multitude of low-mass stars and brown dwarfs. Despite many discoveries from the Deep Near-Infrared Survey of the Southern Sky (DENIS, Epchtein et al. 1999), the Two Micron All-Sky Survey (2MASS, Cutri et al. 2003), and the Sloan Digital Sky Survey (SDSS, York et al. 2000), there has not been a large-scale, systematic effort to study this new regime. In particular, late-M and early-L dwarfs have received relatively little attention while the emphasis has been on pushing detections to lower and lower luminosities and temperatures. We have undertaken a project to compile an all-sky, volume-limited sample (20 pc) of nearby objects with spectral types from M8 to L8. Candidate nearby dwarfs are found using 2MASS infrared photometry and are followed-up with moderate-resolution, far-red optical spectroscopy. Spectral types are used to estimate absolute magnitude and distance. This proceeding is a summary of results in presented in Cruz et al. 2003 and Cruz et al. 2004 (hereafter Paper V and Paper IX) and all references to work discussed here should be made to those papers.

2. The Sample

We culled the 2MASS Second Release (47% sky coverage) using several methods to select all of the M and L dwarfs cooler than M7 within 20 pc. The creation of the sample is discussed in detail in Paper V, however, we briefly summarize the procedures here. The primary selection criteria identified eleven million sources with $|b| > 10°$ and $(J - K_S) > 1$. The sample was narrowed to 1672 objects with the near-infrared color cuts illustrated in Figures 1 and 2, positional coincidence with star formation regions (e.g., Orion, Lupus), dense regions (e.g., LMC, M31), and other reddening regions. The resulting sky coverage is 40%. The 588 objects with $J \leq 9$ were analyzed separately and, based on existing data, no late-type dwarfs were identified amongst them. The remaining 1084 fainter candidates were examined in detail. Visual inspection and cross-referencing with the Guide Star Catalog and SIMBAD eliminated 453 objects, leaving 631 ultracool candidates. Of these, 112 were able to be classified with existing data. The remaining 519 require follow-up observations.

3. Observations

Moderate resolution, far-red spectroscopy for 481 candidates was obtained with NOAO facilities on Kitt Peak and Cerro Tololo and with University of Washington access to the Apache Point Observatory[1]. The instrumental setups and data reduction are described in Paper V.

The follow-up status of the 519 targets requiring observations is shown in Figure 3. Spectral data for 307 objects was presented in Paper V and data for a further 170 objects is in Paper IX. We will present near-infrared data for twenty-seven objects too faint for optical follow-up with 4-m class telescopes in a future paper. Only fifteen objects

[1] Spectra are available upon request from K. L. C, kelle@amnh.org.

Table 1. Summary of new spectroscopic results

Spectral Type	No. found outside 20 pc	No. Found within 20 pc
<M6.5	97	1
M7–M9.5	175	29
L0–L4.5	57	14
L5–L8	10	13
giants	68	
carbon	31	
not M or L	9	

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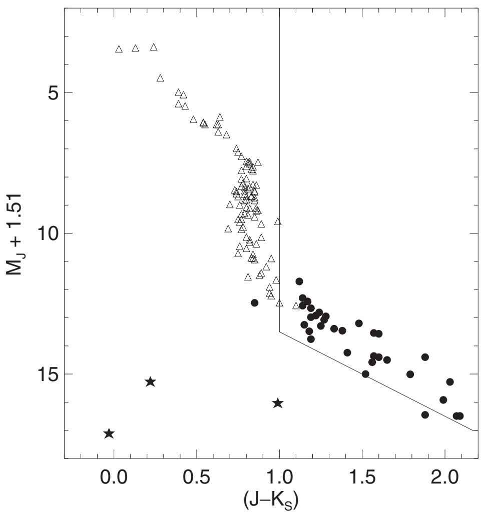

Figure 1. Color-magnitude diagram for low-mass stars with trigonometric parallax measurements shifted to 20 pc with our selection criteria. Triangles are from the 8 pc sample. Data for ultracool dwarfs (M7–L8, filled circles) and T dwarfs (filled five-point stars) are from Dahn et al. (2002). Targets are selected if they lie above and to the right of the cuts.

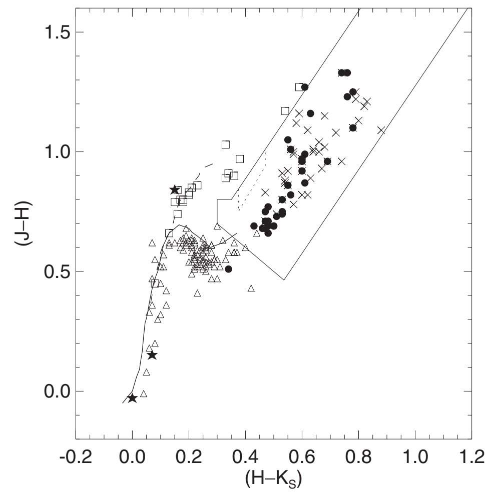

Figure 2. Color-color diagram for the same data (plotted with the same symbols) as Figure 1 and our selection criteria. In addition to objects with trigonometric parallax data, we show L dwarfs from Kirkpatrick et al. (1999, 2000) with uncertainties less than 0.1 magnitudes as crosses and open squares are giants. We also show the dwarf and giant sequences (both from Bessell & Brett (1988), transformed to the 2MASS system). Targets are selected if they lie within the enclosed region. The region where bright objects ($J < 10$) are eliminated as giants is enclosed with a dotted line.

remain with no data—seven are at very southern declinations ($\delta < -60°$) and clumped near either the LMC or SMC while the other eight have $J > 15.9$ and will be targeted for future observations in the near-infrared and in the optical with 8-m class telescopes.

4. Results

The breakdown of the results of spectroscopy is shown in Table 1. We have discovered 56 objects with types M7 and later that appear to be within 20 pc and 242 more distant late-type dwarfs. Spectroscopy has also revealed 68 giants and 31 carbon stars. We have spectroscopy on nine targets that definitively rules out classification as an M or an L dwarf but a spectral type has not yet been determined. The coordinates, spectral types, and distance estimates for all targets are listed in Papers V and IX.

In Figure 4, we show the spectral type distribution of the ultracool dwarfs identified within 20 pc. In most cases, we have doubled the number of objects known, significantly increasing the completion of the census of the Solar Neighborhood. These objects make up the core sample used to estimate the luminosity function as described below.

Spectral types are determined via side-by-side comparison with standard star spectra. The uncertainty on spectral type is ±0.5 subtypes except where low signal-to-noise data result in uncertainties of 1 or 2 types. M_J is estimated by using the spectral type/M_J calibration derived in Paper V and is combined with 2MASS Second Release J-band photometry to yield a spectrophotometric distance estimate. The uncertainties in both the derived M_J and distance are dominated by the uncertainty in the spectral type.

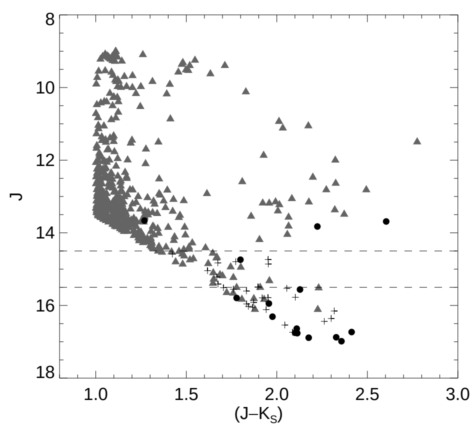

*Figure 3. Status of the follow-up observations of the sample with far-red optical spectra (*triangles*), near-infrared spectra (*plus signs*), and no follow-up (*circles*).*

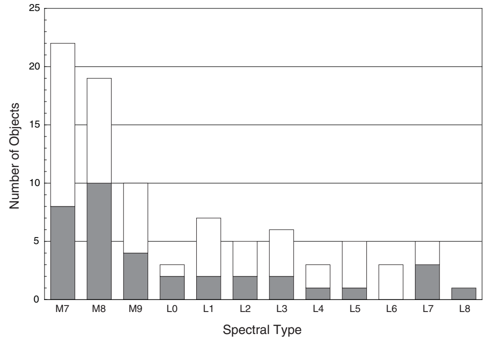

Figure 4. Stacked histogram of the spectral type of all the dwarfs included in the luminosity function estimate. The shaded region indicates objects previously known while the non-shaded region represents our additions to the 20 pc sample.

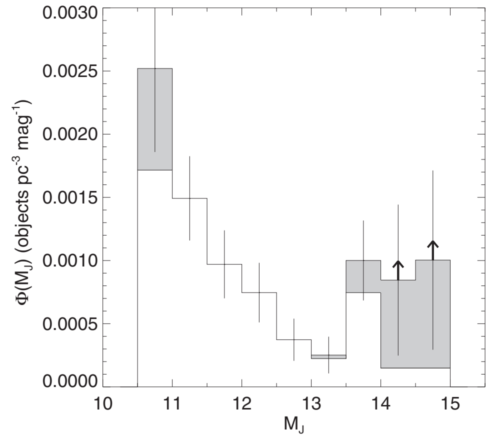

*Figure 5. Our best estimate of the luminosity function distinguishing the raw measured densities (*unshaded*) from the incompleteness-corrected values (*shaded*). We have corrected for observational incompleteness, volume incompleteness, and spectral type incompleteness. Because early and mid-T dwarfs have M_J values corresponding to the faintest two magnitude bins ($14 < M_J < 15$), our measurement is a lower limit on the ultracool dwarf luminosity function.*

5. The Luminosity Function

We identify 89 objects in 86 systems in 40% the sky (2MASS Second Release and $|b| > 10$) with spectral types between M7 and L8 that appear to be within 20 pc of the Sun—we use these to make the first estimate of the ultracool dwarf luminosity function (LF).

The measured luminosity function is essentially complete to $J = 14.5$ (see Figure 3). There are three objects with no observations that have $J < 14.5$, but these are likely to be one distant ($d > 50$ pc) M dwarf and two carbon stars—all three are near the SMC. This completeness limit corresponds to $M_J = 13$ (∼L3.5) at 20 pc. In addition, we are likely missing M7 dwarfs since several are known with $(J - K_S) < 1$, VB 8 is an example. Thus our measured luminosity function is formally complete from spectral types M8 to L3.5. However, as described in detail in Paper IX, we are able to use statistical methods to get a robust estimate of the luminosity function for types M7 to L8.

Our best estimate of the luminosity function (LF) of ultracool dwarfs is shown in Figure 5. There are three main points of discussion: 1) the effect of T dwarfs of the LF, 2) the change to an increasing LF at fainter magnitudes, and 3) how the combined 8 pc sample and ultracool dwarf LF reflect the properties of low-mass stars and brown dwarf evolution. Each of these points is addressed below.

Our estimate of the space densities of late-L dwarfs (L6–L8, $14 < M_J < 15$) is a lower limit on the full ultracool dwarf luminosity function, which includes M, L, and T dwarfs. Recent trigonometric parallax results show that brown dwarfs *brighten* at M_J by as much as one magnitude even though they are actually cooling in temperature as they evolve from L to T dwarfs (Dahn et al. 2002; Tinney, Burgasser, & Kirkpatrick 2003). This brightening is probably due to the clearing of clouds and a lowering of the photosphere. As a result, the space densities of both late-L and early-to-mid T dwarfs (T0–T5) contribute to the luminosity function in our faintest two magnitude bins ($14 < M_J < 15$). Predicted space densities of brown dwarfs based on evolutionary models suggest that there might be as many as ∼80 T0–T5 dwarfs within 20 pc (Burgasser 2004). Since we have only measured the contribution from L dwarfs, our estimates of the space densities of objects with $14 < M_J < 15$ are a lower limit on the full ultracool dwarf LF.

As we first pointed out in Paper V, our measured luminosity function continues to decrease towards fainter magnitudes until $M_J = 13.75$, where it turns around and the space density of ultracool dwarfs begins to increase. Put simply, this implies that the field space density of late-L dwarfs is greater than that of earlier type L dwarfs. As a test of the robustness of our measurement of this turnaround, we consider the possibility that the true luminosity function remains constant from $13.25 < M_J < 14.75$. In this scenario, taking into account our estimated completeness, we would expect to find a total of 3.2 objects in the faintest three magnitude bins. Our detection of 14 objects in these three bins rules out the constant LF at faint magnitudes hypothesis at the 99.9% confidence level. We conclude that we have indeed measured the turnaround to an increasing luminosity function for late-L dwarfs as was predicted by Burgasser (2002) and Allen et al. (2003).

The J-band luminosity function derived from the 8 pc sample (Reid, Gizis, & Hawley 2002) is shown with our best estimate of the ultracool dwarf LF in Figure 6. Both samples are sensitive to late-M dwarfs, and where the two measurements overlap, they agree within the 1σ uncer-

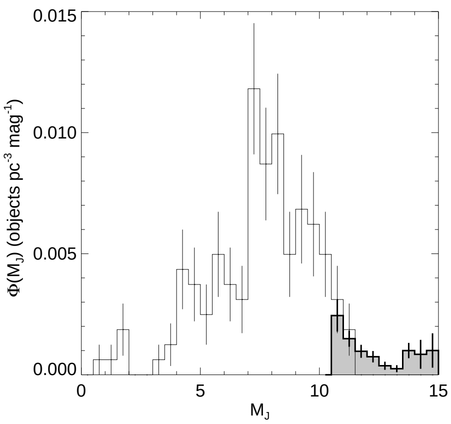

*Figure 6. Our measured J-band luminosity function (*shaded*) with the results from the 8 pc sample (Reid, Gizis, & Hawley 2002).*

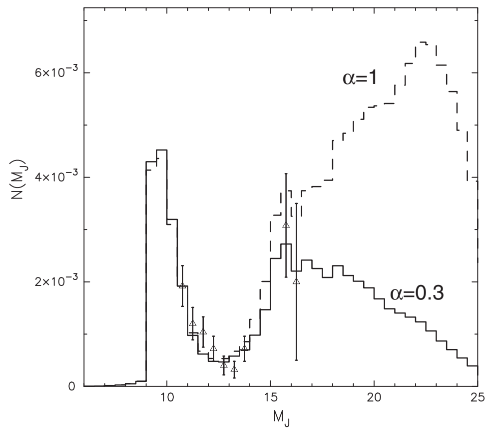

Figure 7. Model J-band luminosity functions (solid and dashed lines) constrained by our space-density data for M and L dwarfs and the T dwarf data from Burgasser (2002). The two model LFs shown are for $\alpha = 1$ (dashed) and $\alpha = 0.3$ (solid).

tainties. The increasing slope of the bright half of the LF ($0 < M_J < 7$) reflects the fact that there are more fainter, less massive stars than brighter, more massive ones in the Solar Neighborhood. Even though we still expect less massive objects to significantly outnumber more massive objects well into the low-mass stars regime, we have measured the LF to be decreasing past $M_J = 7$ (∼M5). This is due to the fact that low-mass stars span a large range of magnitudes but a small range of masses. While the mass changes by $\sim 0.4\ M_\odot$ mag^{-1} for $0 < M_J < 7$, it only decreases $\sim 0.07\ M_\odot$ mag^{-1} for $7 < M_J < 14$.

The space density of all L dwarfs is significantly lower than that of M dwarfs while there are more late-type L dwarfs than that of early-Ls. This is caused by the intrinsically small number of stellar (hydrogen-burning main sequence) L dwarfs and the fact that brown dwarfs remain on the L dwarf sequence for a relatively short period of time. The very lowest-mass stars that appear as L dwarfs (L0–L3) span an extremely small range in mass ($0.075 < M_\odot < 0.085$) and, as a result, are rare. Almost all brown dwarfs appear as L dwarfs during their early stages of evolution. However, they evolve relatively quickly through the hotter, early-L dwarf sequence and, as the rate of cooling decreases at later spectral types, brown dwarfs spend significantly more time as late-L, T, and Y dwarfs.

6. Constraints on the Mass Function

There is no unique mass-magnitude relation for brown dwarfs because they gradually cool with time. As a result, theoretical models must be used to reinterpret the luminosity function as a mass function. Allen, Koerner, & Reid (2004) have used the evolutionary models by Burrows et al. (2001) to create synthetic luminosity functions where the underlying physical parameters are known—we are interested in the exponent of a power-law mass function, α, in particular. We compare our measured ultracool dwarf LF and the T dwarf LF (Burgasser 2002) to model luminosity functions in Figure 7. Overall, the agreement between the theoretical LFs and the data is quite good—the models lie within $\sim 2\sigma$ of the data points. In addition, the general trend for all realistic values of α is a turnaround of the LF in the L dwarf regime with a sparser space density of L dwarfs compared to that of T dwarfs. However, the models appear to be under-predicting the magnitudes of the features present in the luminosity function. Most striking is that we find the base of the trough of the LF to be at $M_J \sim 13.5$ and the models predict it to be at $M_J \sim 12.5$.

Unfortunately, neither our measured L dwarf space densities, nor the currently available T dwarf data, strongly constrain the mass function. While the best fit is for $\alpha = 0.3$, the results are consistent with $0 < \alpha < 1.5$ in the substellar regime. Forthcoming revised T dwarf space densities will likely yield a more robust estimate of α. Not only will these results lend insight into the formation mechanisms of brown dwarfs, they will also yield the expected space density of as-yet-undiscovered Y dwarfs.

7. Conclusions

We have culled the 2MASS Second Release for objects that appear to be ultracool dwarfs within 20 pc of the Sun. Extensive spectroscopic follow-up has led to the discovery of 94 L dwarfs and 204 late-M dwarfs—56 of these are within 20 pc. Combining these data with previously known nearby late-type dwarfs, we have used 89 objects to estimate the luminosity function of ultracool dwarfs in the Solar Neighborhood. This work has more than doubled the local census of ultracool dwarfs and has provided the first robust estimate of the luminosity function of late-type stars and brown dwarfs. This result is the first measurement of the turnaround of the luminosity function of ultracool dwarfs at faint magnitudes and is in general agreement with the predictions of evolutionary models; however, this result does not put strong constraints on the substellar mass function.

Acknowledgements

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