THE LUMINOSITY AND MASS FUNCTIONS AT THE BOTTOM OF THE MAIN SEQUENCE

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ABSTRACT. A 270 square degree survey for Very Low Mass (VLM - $M < 0.2M_\odot$) stars in the field is discussed. The major pitfalls encountered in the survey are covered, as well as the major results. In particular, it was found that: 1) no significant difference is seen between the luminosity function for VLM stars as measured by photometric and trigonometric selection criteria; 2) the luminosity function does *not* show a significant increase below $M_{bol} = 13$, 3) the mass function for VLM stars shows significant structure in the VLM regime; and 4) it is hard to envisage a significant amount of missing mass in the disk being in the form of brown dwarfs.

1. The Survey

A detailed description of the techniques used in our survey can be found in Tinney et al. (1993d, Paper I) and Tinney (1993b, Paper IV) — the following is a brief summary. A photometric catalogue of VLM candidates was constructed using IIIa-F and IV-N plates from 11 fields acquired with either the 48″ Oschin Telescope as part of the Palomar Observatory Second Sky Survey (POSS II), or the 48″ Anglo-Australian Observatory Schmidt Telescope (AAOST) as part of the UK Science Research Council's Southern Sky Survey (UKSRC). These plates were scanned on the COSMOS machine at ROE, and calibrated using extensive CCD sequences acquired on the Palomar 60″ telescope. The catalogue of VLM candidates was constructed by selecting stars in the colour range $(R - I)_C \sim 2.2 - 2.7$, and aimed at detecting all VLM stars in our survey area, down to $I \approx 17$.

It should be noted that these optically-selected very red stars were only considered as a list of VLM *candidates*. Because of uncertainties in the photographic photometry, and the fact that optical colours are intrinsically poor estimators of luminosity for these faint stars (which emit most of the flux in the IR), infrared follow-up is essential for estimating precisely their luminosity — and so their mass. We found that the measured R - I colours from our plates only sufficed to estimate M_{Bol} to within ±1.5 mag., whereas I - K colours (Tinney et al. 1993a, Paper III) allow M_{Bol} estimates as good as ±0.3 mag. The photographically selected samples are also subject to serious contamination by spurious images and galaxies for the very faintest stars — again requiring follow-up observation to remove contamination from the VLM sample (see Paper I).

Samples of VLM candidates were therefore selected in each POSS II/UKSRC field, and observed at the K-band using the infrared cameras on the Palomar 200″, Las Campanas 100″ and

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NASA IRTF telescopes. In all, IR photometry was acquired for almost 500 VLM candidates. We could then use the photographic I-band photometry and the IR K-band photometry to construct an I - K colour for each star. Bolometric luminosities were estimated from (I-K) using the relations of Paper III, and a bolometric luminosity function was constructed.

2. The Luminosity Function

The results of this are summarised in Figs. 1a and 1b. Both figures show (in two binnings) the bolometric luminosity function (LF) determined from our photographic data alone for $M_{bol} = 8 - 12$ (*open circles and triangles*). Below $M_{bol} = 12$ the photographic data become seriously contaminated, and in this range the LF shown has been constructed from our photographic-infrared data (*open circles and crosses* — see Papers I and IV for details of the LF construction). In all cases, the uncertainties shown are based on Poisson counting errors. The last two points in each figure are 1-σ upper limits.

Figure 1a compares the results of our survey with those of previous studies based (like ours) on samples selected by photometric criteria from 48″ Schmidt plates. The *filled squares* are the LF of Hawkins & Bessell (1988), and the *filled circles* are the LF of Reid (1987). The most important point to note is the apparent increase in the number density of very faint stars seen in the Reid data has been shown to be due to contamination of the samples used (IR follow-up was not available for some of those data). The Hawkins & Bessell data are consistent with ours. Figure 1b shows the comparison of our data with that of Weilen et al. (1983 — *filled squares*) and Henry & McCarthy (1990 — *filled circles*) — both samples having been constructed from nearby stars with measured parallaxes. There has been considerable debate in recent years over the apparent disagreement between the data of Weilen et al. (1983) and the available photometrically-selected LFs. In particular, Weilen et al. (1983) claimed they saw no evidence for a decrease in their LF beyond $M_{bol} = 10$, while Henry & McCarthy (1990) claimed their data showed only an increase in the LF beyond $M_{bol} \approx 11$. However, as Fig. 1b shows, when the

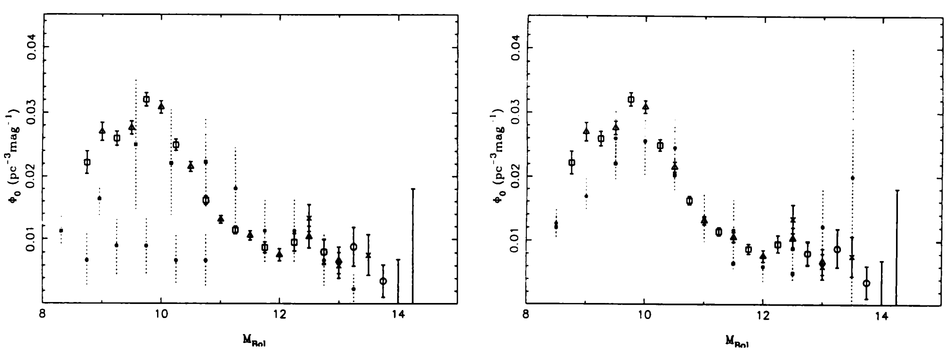

Figure 1. Bolometric Luminosity Functions, **a)** compared to previous photometric studies, and **b)** compared to previous trigonometric sample LFs.

Henry & McCarthy data are normalised by the volume sampled, no significant difference is seen for the faintest stars between their data and ours. It would appear that the photometric versus trigonometric LF debate has been somewhat of a chimera.

3. The Mass Function

Of course, the function of most interest is the mass function (MF) for these stars, since it is the extrapolation of the MF which will tell us the most about the amount of mass 'hidden' in the solar neighbourhood in the form of brown dwarfs. Unfortunately, the interpretation of the LF in terms of an MF is not trivial. At present, reliable empirical masses have only been determined for stars down to $M \approx 0.1M_\odot$. We are therefore forced to rely on theoretical mass-luminosity relations if we are to convert the observed LF for $M_{bol} \lesssim 12$ into an MF. Moreover, these stars also undergo luminosity evolution. Because they lie in the 'transition region' between purely H-burning main sequence stars, and purely contracting brown dwarfs, they derive part of their luminosity from nuclear burning, and part from gravitational contraction — over timescales of several Gyrs they can change their bolometric luminosities by many magnitudes. In the absence of age estimates for these stars, we can therefore gain only a crude handle on their MF. In Fig. 2 we show the MFs constructed from our LF for two assumed models — a 10 Gyr and a 1 Gyr model due to Burrow et al. (1989 — BHL). In each case we have extended the mass-luminosity relation to larger masses than the BHL models covered, using an empirical relation due to Smith (1983). These two models will to some extent 'bracket' the likely age range present in our sample of disk stars. The major difference between the results for older and younger stars, is that the younger stars have a less steep turn-over in the mass-luminosity relation below $0.1\ M_\odot$, which results in stars being spread to lower masses in the 1 Gyr MF.

In any case, a number of features can be seen independent of age assumptions. First, and most dramatically, the mass function below $0.3M_\odot$ *is not a power law*. In particular, it is not a Salpeter power law! A turn-over is seen in the mass function at $\approx 0.2M_\odot$ — clearly in our data, though it was also indicated in the earlier results of Reid (1987) and Scalo (1986). There is also evidence for an increase in the MF beyond the minima at $\approx 0.1M_\odot$ — which is seen regardless of the model chosen (see Paper IV). However, it should be noted that this increase is completely due to the fact that the mass-luminosity relation steepens in this region. The LF for $M \lesssim 0.15M_\odot$ is completely flat. And while we *know* that the mass-luminosity relation must be steepening in this region, and that the increase in the MF is very probably real, we must be very careful about drawing conclusions as to the slope of the MF for $M \lesssim 0.1M_\odot$.

Lastly, we can use the much improved number statistics this survey has produced for $M \approx 0.1M_\odot$, to attempt to estimate how much mass may be hidden below the H-burning limit. Table 1 shows the integrated mass density in the solar neighbourhood given the measured mass density of $0.45M_\odot^{-1}pc^{-3}$ at $0.1M_\odot$, for a range of assumed minimum masses and power-law mass functions. It can be seen that the range of parameter space available which produces a *significant* amount of missing mass (0.05 - $0.1M_\odot pc^3$ is very small — either a mass function significantly steeper than that seen anywhere else on the main sequence, or a minimum mass significantly lower than that currently thought likely (Boss 1986). It seems difficult to envisage either situation being the case.

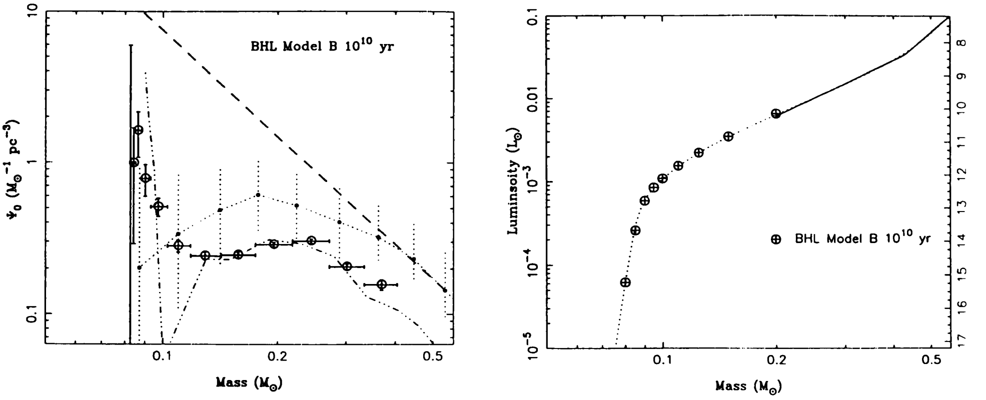

Figure 2a.

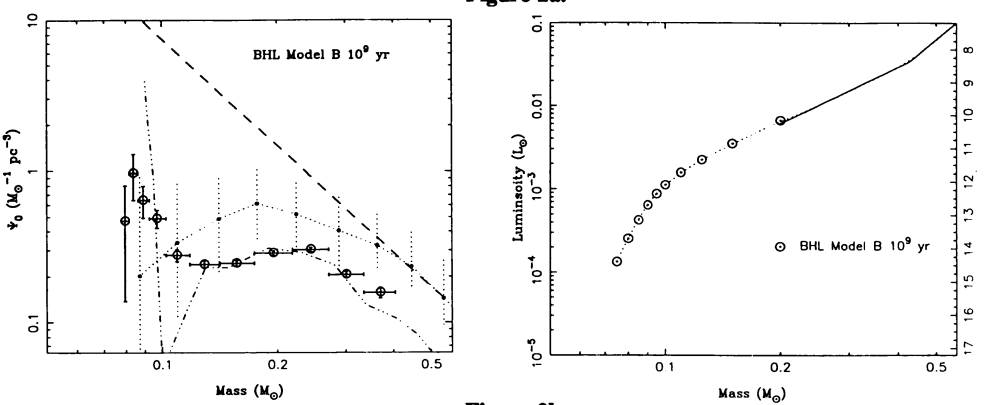

Figure 2b.

Figure 2. The leftmost panel of each figure shows the MF constructed from our data using the mass-luminosity relation shown in the rightmost panel. In each figure the MFs due to Scalo (1986 — *solid circles*) and Reid (1987 — *dot-dashed line*) are shown. The Salpeter MF is also shown, arbitrarily normalised to the Scalo MF at $0.5M_\odot$.

4. Conclusions

To summarise the main conclusions of this work: photographic (or indeed CCD) optical data alone are *not* sufficient for studies of these very red, very faint stars — infrared data are essential; the debate in recent years over the 'difference' between the photometrically- and trigonometrically-selected LFs has been somewhat of a mare's nest; the MF for VLM stars is *not* a power law and shows significant structure in the VLM mass range (to digress briefly, this structure — the like of which is seen nowhere else on the main sequence — must be telling us something about the star formation process. The examination of this whole question has been one, unfortunately, largely ignored by workers on VLM stars); and a simple-minded extrapolation of the MF below 0.1M$_\odot$ makes it hard to see how a significant amount of missing mass can be hidden in the solar neighbourhood in the form of brown dwarfs.

Table 1. Solar neighbourhood mass densities for arbitrary mass functions below 0.08M$_\odot$

k	Mass Densities (M$_\odot$pc^{-3})				
	$\int_{0.04}^{0.08}$	$\int_{0.02}^{0.08}$	$\int_{0.01}^{0.08}$	$\int_{0.005}^{0.08}$	$\int_{0.001}^{0.08}$
0	0.0011	0.0014	0.0014	0.0014	0.0014
1	0.0018	0.0027	0.0032	0.0034	0.0036
2	0.0031	0.0062	0.0094	0.125	0.020
2.35	0.0042	0.010	0.018	0.030	0.080
3	0.0056	0.017	0.039	0.084	0.44
4	0.011	0.053	0.221	0.90	22.5

References

Boss, A.P., 1986. 'Astrophysics of Brown Dwarfs', eds. M. Kafatos et al., Cambridge University Press, p. 206.

Burrows, A., Hubbard, W.B. and Lunine, J.J., 1989. *Astrophys. J.*, **345**, 939 (BHL).

Hawkins, M.R.S. and Bessell, M.S., 1988. *Mon. Not. R. astron. Soc.*, **234**, 177.

Henry, T.J. and McCarthy, D.W., 1990. *Astrophys. J.*, **350**, 334 (HM90).

Reid, I.N., 1987. *Mon. Not. R. astron. Soc.*, **225**, 873.

Scalo, J.M., 1986. *Fund. Cosmic. Phys.*, **11**, 1.

Smith, R.C., 1983. *Observatory*, **103**, 29.

Tinney, C.G., 1993a. *Astron. J.*, **105**, 1169 (Paper III).

Tinney, C.G., 1993b. *Astrophys. J.*, **414**, 279 (Paper IV).

Tinney, C.G. et al., 1993c. *Astron. J.*, **105**, 1045 (Paper II).

Tinney, C.G. et al., 1993d. *Astrophys. J.*, **414**, 254 (Paper I).

Weilen, R., Jahreiss, H. and Kruger, R., 1983. 'The Nearby Stars and the Stellar Luminosity Function', IAU Coll. No 76, eds. Davis, Philip and Upgren, Davis Press, Schenectady, p. 163 (WJK).

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