Mem. S.A.It. Vol. 76, 259

Memorie della

New VLM members of southern star forming regions ⋆

Belén López Martí[1], Jochen Eislöffel[2], Reinhard Mundt[3] and Alexander Scholz[2]

[1] Departament d'Astronomia i Meteorologia, Universitat de Barcelona, Martí i Franquès 1, 08028 Barcelona, Spain e-mail: blopez@am.ub.es
[2] Thüringer Landessternwarte, Sternwarte 5, 07778 Tautenburg, Germany
[3] Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany

Abstract. We report on an optical multiband survey for very low-mass stars and brown dwarfs in southern star forming regions with the Wide Field Imager (WFI) at the ESO/MPG 2.2m telescope on La Silla Observatory (Chile). In Chamaeleon I and Lupus 3, a large number of such objects are found. For the first cloud, an index $\alpha = 0.6 \pm 0.1$ is derived for the low-mass IMF, in very good agreement with the results in other young clusters. In contrast, in Chamaeleon II we found only one possible member.
The observations indicate that brown dwarfs and stars have similar levels of Hα emission, suggesting mass accretion. In Chamaeleon I, this emission is related to the presence of an ISOCAM mid-infrared excess, a signature of circum(sub)stellar disks. On the other hand, no such relation is found between Hα emission and near-infrared excess in any of the regions, probably because signatures of disks are difficult to detect at these shorter wavelengths. Brown dwarfs and stars also have a similar spatial distribution, being clustered near the cloud cores. This contradicts the ejection picture of brown dwarf formation, unless dynamical interactions between cluster members are strong enough to retain the ejected stellar cores within the clouds.

Key words. stars: low-mass, brown dwarfs – stars: pre-main sequence – stars: formation – stars: luminosity function, mass function – stars: circumstellar matter

1. Introduction

Surveys for very low-mass stars and brown dwarfs in star forming regions are of great importance to understand the formation and early evolution of these objects, as well as to address the problem of the universality of the low-mass initial mass function (IMF). Young brown dwarfs (age$\lesssim$10 Myr) are relatively bright, and hence detectable even at optical passbands. However, such surveys are not exempt from problems, because there is no direct test to the substellar nature of these objects (The Lithium test cannot be applied at this early stage of evolution). Thus, we have to rely on the predictions from the theoretical models (e.g. Baraffe et al. 1998; Chabrier et al. 2000), very uncertain for such young ages. Moreover, contamination with older, extincted field stars is important at such faint magnitudes and red colours. In spite of these caveats, during the

Send offprint requests to: B. López Martí

⋆ Based on observations collected at the European Southern Observatory, La Silla, Chile last decade many surveys have succeeded in providing bona-fide brown dwarfs and brown dwarf candidates in star forming regions and young clusters (e.g. Béjar et al. 1999; Wilking et al. 1999; Barrado y Navascués et al. 2001, Martín et al. 2001). Nonetheless, with the few exceptions of some rich and well studied Orion clusters, the statistics of substellar objects in these regions are still very incomplete, and the influence of the environment in the formation of brown dwarfs is far from being understood.

In this contribution, we report on our own survey campaign for brown dwarfs in Chamaeleon I and II, and Lupus 3, three well-known star forming regions of similar age (1-5 Myr) and distance (140-200 pc).

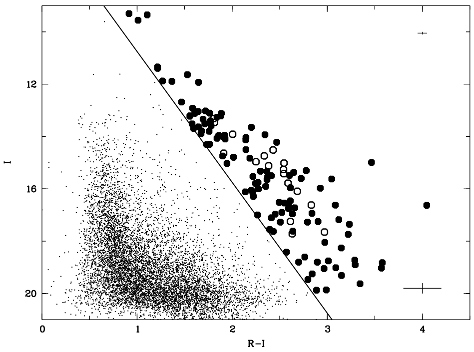

Fig. 1. Example of an (I, R–I) colour-magnitude diagram for one of our surveyed regions: In Chamaeleon I, brown dwarf candidates (solid symbols) are selected around the position of the empirical isochrone defined by previously known low-mass stars and brown dwarfs (Comerón et al. 2000; open symbols).

2. Observations

Our observations were performed using the Wide Field Imager (WFI) mosaic camera at the ESO/MPG 2.2m telescope on La Silla Observatory (Chile). For the purpose of candidate selection, images were taken in two broad-band filters, R and I, in a narrow-band filter centred in the Hα emission line (Hα/7). We also observed in two medium-band filters, M855 (855/20) and M915 (915/28). A spectral type calibration method was developed using the correlation of the M855–M915 colour with the M4-M9 and early-L subspectral types (see López Martí et al. 2004 for a detailed explanation).

We observed an area of about 1.2 □° in Chamaeleon I (four WFI fields) and of about 1.6 □° in Lupus 3 (five WFI fields), covering the densest parts of these dark clouds. In Chamaeleon II, only one WFI field was observed (about 0.3 □°), placed towards the north-western part of the cloud.

In addition, we made use of available infrared photometry from previous works (Cambrésy et al. 1998; Persi et al. 2000; Vuong et al. 2001; Gómez & Kenyon 2001; Kenyon & Gómez 2001; Persi et al. 2003) and from the 2MASS survey as a complement to our optical photometry.

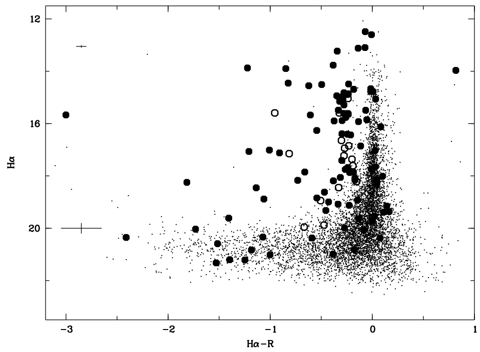

Fig. 2. Example of a (Hα, Hα–R) colour-magnitude diagram. Symbols as in Fig. 1. Hα emitters are found to the left of the main locus of the objects in the surveyed area.

3. Candidate Selection

Candidate members were selected around a cloud isochrone in a (I, R–I) colour-magnitude diagram. In Chamaeleon I (see Fig. 1), this isochrone was defined by previously known brown dwarfs and very low-mass stars in the region (Comerón et al. 2000). In Lupus 3 and Chamaeleon II, however, there was no sample of known brown dwarfs that could be used for this purpose. Therefore, we had to rely on the

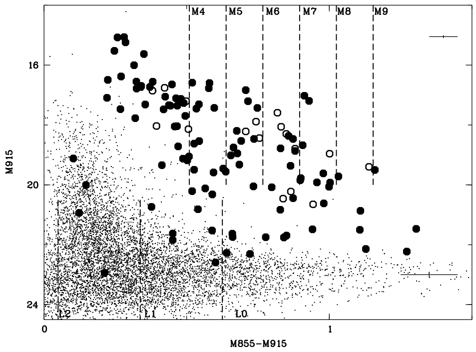

Fig. 3. Example of a (M915, M855–M915) colour-magnitude diagram. Symbols as in Fig. 1. Our scale for the identification of the spectral type is also indicated. The faintest objects in the diagram are regarded as possible L-type objects.

theoretical models in these cases (López Martí et al. 2005a, b).

To confirm the youth of our objects, we tested their Hα emission in a (Hα, Hα–R) colour-magnitude diagram: In general, the bluer (i.e., more negative) the Hα–R colour, the stronger the Hα emission (see López Martí et al. 2004). As an example, Fig. 2 shows the (Hα, Hα–R) colour-magnitude diagram for our Chamaeleon I survey.

A first spectral type classification was provided from the position of our objects in a (M915, M855–M915) colour-magnitude diagram. Fig. 3 shows this diagram for Chamaeleon I. The theoretical models place the stellar/substellar boundary at spectral types around M6 (e.g. Chabrier et al. 2000). Following this criterion, we identified 69 new probable members of the Chamaeleon I cloud (42 stars and 27 brown dwarf candidates) and 21 of Lupus 3 (16 stars and 6 brown dwarf candidates). In Chamaeleon II, only one object, a candidate low-mass star, shows clear Hα emission. However, its spectral type could not be determined by means of our photometric calibration; given its blue M855–M915 colour, it must be a relatively early-type star.

Finally, we cross-correlated our full candidate list in every region with available near- and mid-infrared catalogues from previous works, with the aim to further confirm the youth of our Hα emitters, and also to eventually identify other cloud members without Hα emission. To this purpose, several colour-colour magnitude diagrams were constructed to look for infrared excesses (Fig. 4 shows two examples). In this way, three objects (two stars and a brown dwarf candidate) were added to the candidate list in Chamaeleon I, and one (a faint brown dwarf candidate) to that of Lupus 3. No additional members of Chamaeleon II could be identified.

4. Results

4.1. Spatial Distribution and Visual Binaries

The new very low-mass members of Chamaeleon I and Lupus 3 are placed near the cloud cores, with no signs of luminosity segregation. This distribution contradicts the hypothesis of brown dwarfs being stellar embryos ejected from their parental systems (Reipurth & Clarke 2001) unless, as argued by Kroupa & Bouvier (2003), dynamical interactions between the cloud members are able to keep the ejected brown dwarfs within the clusters.

With a few exceptions, all our objects are found in isolation. In Chamaeleon I, only two pairs star-brown dwarf candidate are seen at distances lower than expected from a random distribution of the objects in the field, and thus may form wide binary pairs. In addition, one brown dwarf candidate in Chamaeleon I and two in Lupus 3 are found near a previously known T Tauri star. However, given the wide separation between the two components of all these visual pairs, the probability that they are true physical binaries is low.

4.2. Accretion Disks

Many of our new Chamaeleon I members had been detected by ISOCAM (Persi et al. 2000). The left panel in Fig. 4 shows a plot of the colour index defined by these passbands, $m(6.7) - m(14.3)$ versus our measured Hα–R colour. All our objects with strong Hα emis-

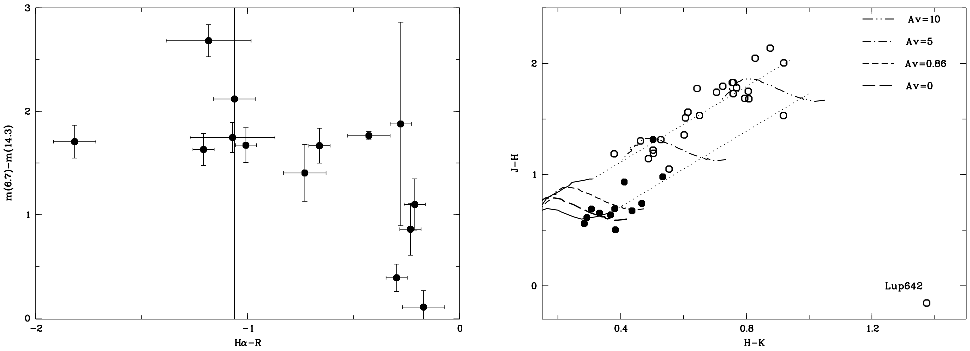

Fig. 4. *Left panel*: (Hα–R, m(6.7)–m(14.3)) colour-colour diagram for the objects in our Chamaeleon I sample detected by ISOCAM in both passbands (Persi et al. 2000). The objects with very strong Hα emission have mid-infrared excess. *Right panel*: 2MASS $(J-H, H-K)$ colour-colour diagram for our candidates with near-infrared photometry in Lupus 3. Objects with and without Hα emission are marked with solid and open symbols, respectively. The solid curves indicate the locus of dereddened dwarfs and giants according to Bessell & Brett (1988). The dotted lines indicate the direction of the reddening vector up to $A_V \sim 10$ mag. The other lines indicate the position of a 1 Myr isochrone from the models of Baraffe et al. (1998) for different extinction values.

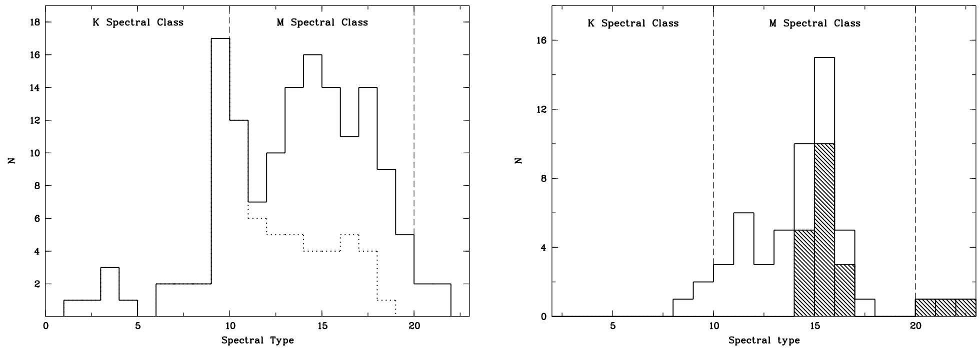

Fig. 5. *Left panel:* Histogram showing the distribution of spectral types for all known low-mass stars and brown dwarfs in our surveyed area in Chamaeleon I. The dotted line is the distribution for the objects studied by previous authors (Gauvin & Strom 1992; Lawson et al. 1996; Comerón et al. 1999, 2000). *Right panel:* Spectral type distribution for ours and the previously known members (from Hughes et al. 1994; Comerón et al. 2003) in our surveyed area in Lupus 3. The shaded histogram corresponds to the objects identified in our survey.

sion detected in both ISOCAM passbands are found to have a mid-infrared excess. Hence, it seems that they are surrounded by circum(sub)stellar disks, and that their Hα emission is mostly caused by accretion processes.

The relation between a blue Hα–R colour and a mid-infrared excess could not be tested in the other two regions, since none of our objects in Chamaeleon II had been detected by ISOCAM (Persi et al. 2003), and no mid-infrared observations were available for Lupus 3. Nonetheless, we note that the levels of Hα emission from our objects are very similar in the three clouds, which hints to a common origin for this emission.

On the other hand, it was not possible to establish a relation between the Hα–R colour index and a near-infrared excess for any of the three regions. Indeed, as first noted by Natta & Testi (2001), the presence of disks around such cool objects is difficult to infer from near-infrared photometry alone, where the emission is largely dominated by the photosphere. However, in some cases the presence of a near-infrared excess allowed to confirm as members objects that showed no clear Hα emission. This is the case of Lup 642, a faint brown dwarf candidate in Lupus 3 (see right panel in Fig. 4).

4.3. Spectral Type Distribution and Mass Function

Fig. 5 shows the spectral type distribution for all the objects known so far in our surveyed fields in Chamaeleon I and Lupus 3. Note that the represented samples are somewhat incomplete at early-M spectral types, because our photometric method does not allow to classify objects earlier than M4.

In the case of Chamaeleon I, two peaks are seen. The higher one corresponds to spectral types around K7, in agreement with the results from previous authors (e.g. Gauvin & Strom 1992). The second peak is found around spectral type M4. For Lupus 3, a single clear peak is placed at spectral types around M5. This result also agrees with the known properties of the cloud, characterised by its large number of late-type stars (e.g. Hughes et al. 1994).

For Chamaeleon I, the number of objects below the substellar limit was large enough to allow us an estimation of the index α of the usual approximation for the IMF towards lower masses ($dN/dM \sim M^{-\alpha}$). With our data, we obtain for this dark cloud:

$$\alpha = 0.6 \pm 0.1$$

This value is in very good agreement with the results in other young clusters and star forming regions (e.g. Moraux et al. 2003; Béjar et al. 2001; Tej et al. 2002).

5. Discussion and Conclusions

While the very low-mass population of Chamaeleon I and Lupus 3 seems to be important, no very low-mass objects are identified in Chamaeleon II. This result might be a consequence of the properties of this latter region, which is presumably at an earlier stage of evolution than the other two, and contains more embedded than visual objects (Gauvin & Strom 1992). We note, however, that the surveyed area in Chamaeleon II was relatively small in comparison with the other two regions, covering only part of a cloud core to the north-west. In contrast, our observations in Chamaeleon I and Lupus 3 covered most of these clouds. It cannot be excluded, thus, that surveys in other areas of Chamaeleon II may unveil a young brown dwarf population so far unknown.

The similar Hα emission and accretion properties of stars and brown dwarf candidates support the picture of a similar formation process. Moreover, the new identified members in Chamaeleon I and Lupus 3 tend to be clustered near the cloud cores, contradicting the ejection picture of brown dwarf formation, unless dynamical interactions are enough to retain the substellar objects within the cluster.

For the Chamaeleon I population, we derive an index $\alpha = 0.6 \pm 0.1$ for the low-mass IMF, which is in very good agreement with the estimations in other star forming regions and young clusters.

Acknowledgements. We kindly thank C. Bailer-Jones for his help with the field selection, and E. Pompei and the 2p2-team for their support during the observations. We are also very grateful to P. Persi for providing us the complete list of the ISOCAM observations in Chamaeleon. This work was supported by the German *Deutsche Forschungsgemeinschaft, DFG* projects number EI 409/7-1 and EI 409/7-2.

This publication makes use of data products from the Two Micron All Sky Survey (2MASS), a joint product of the University of Massachussets and the Infrared Processing and Analysis Centre/California Institute of Technology, funded by the US National Aeronautics and Space Administration and the US National Science Foundation.

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