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Wide-field observations of southern star forming regions ⋆

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Abstract. We present preliminary results on the identification of low-mass Pre-Main Sequence stars and young brown dwarf candidates using wide-field techniques in the star forming regions in L1616, Chamaeleon II and the Southern Cross. Spectroscopic follow-up observations in L1616 show that some of the candidates are very likely young brown dwarfs. We discuss the possibility to perform wide-field imaging surveys with VST in order to significantly increase the number of young BD candidates for IMF studies in the sub-stellar regime.

Key words. IMF – Stars: Pre-Main Sequence – Young Brown Dwarfs – Wide-Field Imaging

1. Introduction

The determination of the Initial Mass Function (IMF), which is an important issue for the understanding of the star and planet formation process, is still under debate, in particular in the very low-mass (VLM) and sub-stellar regimes. Recent investigations give controversial results. While in the Orion OB association the IMF appears to rise for masses below 0.1 $M_\odot$ (Hillenbrand & Carpenter 2000), in T associations like Taurus-Auriga there is evidence of a deficit of sub-stellar objects (Luhman 2000; Briceño et al. 2002). Other studies of the young cluster IC 348, which is devoid of very massive stars, have also revealed a deficit of BDs relative to the Orion Nebula Cluster (Preibisch et al. 2003; Muench et al. 2003).

The inconsistencies in the sub-stellar IMF may be ascribed to the following reasons:

i) the census for sub-stellar objects is rather incomplete due to the fact that the surveys for such objects concentrate in sharply selected sky areas, in particular in the cores of SFRs;

ii) many sub-stellar objects might have been ejected from their birth sites and hence, might have escaped detection in the "pencil-beam" surveys in SFRs. Dynamical interactions in young multiple systems may lead to the ejection of objects before they can reach stellar masses (Reipurth & Clarck 2001). The studies by Sterzik & Durisen (2003) suggest ejec-

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⋆ Based on observations collected at the ESO-VLT Proposals 70.C-0536(A) and 70.C-0629(B)

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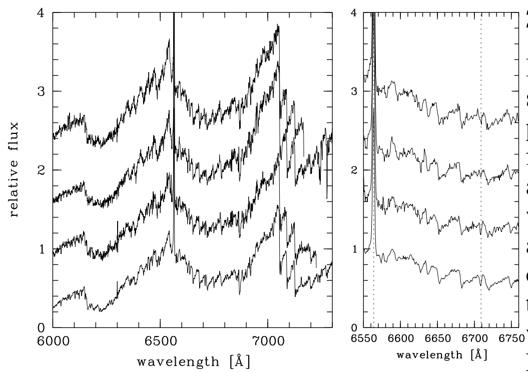

Fig. 1. Examples of young BD spectra in the cometary cloud L1616 in Orion. An enlarged plot in the range of Hα – Li I λ6708Å is shown in the right panel. The Hα emission and Li I absorption lines are indicated with the dotted lines.

tion velocities for BDs of less than 2 km s^{-1}. In about 1 Myr, such objects would move about 2 pc (i.e. some 0.°25 in the sky at the distance of 450 pc) from their birth sites.;

iii) alternatively, different environments might produce different initial conditions for star and planet formation and, hence, might lead to different mass spectra in different SFRs. For instance, the radiation and winds of OB stars or supernova shock waves that may trigger star formation in OB associations may also have an important impact on the mass accretion during the formation process. While in a T association a protostar may accumulate a significant fraction of mass, the mass accretion of a low-mass protostar in a region exposed to the winds of OB stars or supernova shock waves can be terminated abruptly because of the photo-evaporation of the circumstellar matter (Kroupa 2001, 2002). Therefore, many low-mass protostars may not complete their accretion and hence can result as substellar objects.

One way to tackle these issues is by means of multi-wavelength studies in wide areas in SFRs. In this contribution, we present preliminary results of wide-field observations in the star forming regions in L1616, the Chamaeleon II dark cloud and the Southern Cross.

2. The L1616 cometary cloud

In order to characterize this region (located south-west of the Orion OB association, at a projected distance of about 60 pc), we performed a multi-wavelength study (Alcalá et al. 2004). Several new low-mass PMS stars were discovered. Also, many VLM PMS stars and young BD candidates were selected based on color-magnitude diagrams. After the identification of the candidates will be completed, we expect to find a number of young BDs in L1616 intermediate between that of Taurus and the Orion Trapezium. Star formation in L1616 was most likely triggered by the impact of the winds of the massive stars of the Orion OB association. Therefore, it is interesting to study the mass spectrum in the sub-stellar regime in such environment. For this aim, we have performed a first spectroscopic follow-up of the selected candidates using FORS2 at the VLT-UT4. Additional new PMS members were discovered and four of them are very good candidates to young BDs. The spectra of these objects are shown in Fig. 1. The spectroscopic follow-up in this region is being continued using VIMOS at the ESO VLT.

3. Chamaeleon II

The T association in Cha II is characterized by a number of low-mass PMS stars and embedded objects. An important issue is that the spectral type distribution of its members seems to peak for very low mass stars. Our previous X-ray observations in Cha II show that the Cha II stars are typically less X-ray luminous than those in Cha I (see Fig. 5 by Alcalá et al. 2000). This result, together with the strong dependence of the X-ray luminosity on stellar mass (e.g. Feigelson et al. 1993), is consistent with the fact that the mass spectrum in the Cha II cloud is biased towards less massive stars. The exceptional mass spectrum of the known members of Cha II is an indication that an unprecedented number of VLM stars are still to be discovered in the region and offers the opportunity to search for young BDs and to study the stellar IMF below the Hydrogen-burning limit.

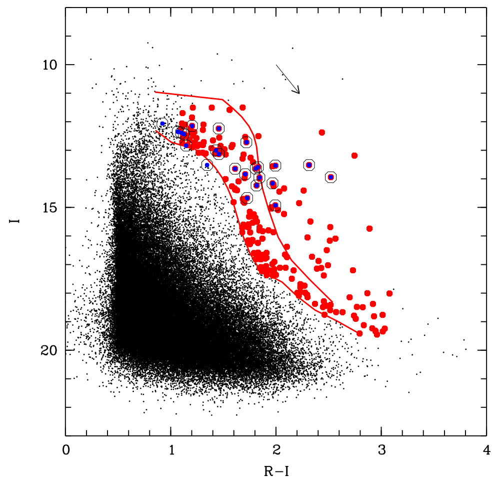

Fig. 2. I versus $(R - I)$ diagram for the point-like objects extracted from the WFI images in Cha II. The continuous lines represent the theoretical PMS isochrones by Baraffe et al. (1998) for 1 and 10 Myr, respectively. The arrow represents the reddening vector.

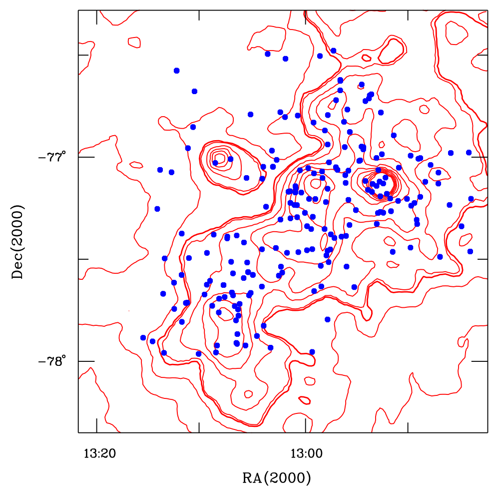

Fig. 3. Spatial distribution of the candidates selected in Fig. 2 (dots) overplotted on the 100μ IRAS contour map in Cha II.

We have performed an optical survey in this region using the Wide-Field Imager (WFI) at the ESO 2.2m telescope in the R, I, z broad bands and also in the Hα, the 856 nm and 914 nm intermediate-band filters. The data reduction is being performed as described in Alcalá et al. (2002b). Our surveyed area is about 2 square degrees and covers almost entirely the SFR. As in previous works (e.g. Alcalá et al. 2004), we use color-magnitude diagrams in order to pre-select PMS star and young BD candidates.

Fig. 2 shows the I vs. $R - I$ diagram of the Cha II region. More than 120,000 sources are revealed in our survey. The already known PMS stars, represented with circled dots in Fig. 2, are used to define the PMS locus in the diagram. The big dots represent objects above the 10 Myr isochrone. Some 200 candidates are selected and about 30% of them might be sub-stellar objects. The candidates tend to follow closely the lanes of the IRAS 100μm dust emission (c.f. Fig. 3). Of course many of these objects might be foreground contaminating objects and the selected sample need to be investigated spectroscopically. From our Hα data we find that about 50% of the candidates may exhibit emission. More details on these results will be published elsewhere.

4. The Southern Cross

Some of the stars in this region have also been characterized by us in previous spectroscopic and photometric observations (Alcalá et al. 2002a).

Using WFI at the ESO 2.2m telescope, we have also surveyed this region to preselect low-mass PMS candidates. An area of 0.25 square degrees was covered in the B, V, R, and I photometric bands. The I vs. $(R - I)$ color-magnitude diagram is shown in Fig. 4. As can be seen, there are only a handful of young BD candidates. Whether this is real or is due to the fact that we might have missed many objects in our survey[1] is not clear at present. More WFI observations are needed in order to clarify this issue.

[1] Note that the region is at a distance of 110 pc and the area surveyed is small

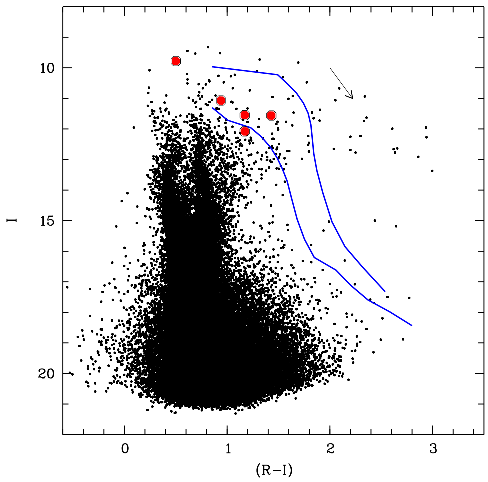

Fig. 4. I versus $(R-I)$ diagram for the point-like objects extracted from the WFI images in the southern cross region. The continuous lines represent the theoretical PMS isochrones by Baraffe et al. (1998) for 1 and 10 Myr, respectively, shifted to a distance modulus of 5.2 (d=110 pc). The big dots represent low-mass PMS stars characterized (see Alcalá et al. 2002a).

5. Prospects for the use of VST in the search for young BDs

It is expected that surveys in star forming regions with the VLT-Survey-Telescope (VST), in the optical, and the Visibile & Infrared Survey Telescope for Astronomy (VISTA), in the near infrared, will provide a wealth of data suitable for the search of young brown dwarfs. We foresee to perform studies with VST in the r', i', z and Hα bands in wide areas of star forming regions. The selection of the candidates will be also based on color-magnitude diagrams, as well as on Hα data.

5.1. Is it possible to use VST for the search for young BDs?

As described in the previous chapters, the selection of the candidates is based on theoretical isochrones on color-magnitude diagrams. However, the form of the isochrones may vary significantly from one photometric system to another. In Baraffe et al. (1998) the isochrones for the Bessel filters are provided. Hence, one should be careful when using a different photometric system. Since for VST the Sloan filters will be implemented, we have performed a feasibility study in order to verify whether we can use the VST system for the identification of the candidates. For this aim we determine VST synthetic magnitudes, $m_{\Delta\lambda}$, by means of:

$$m_{\Delta\lambda} = -2.5 \cdot log_{10}(f_{\Delta\lambda}) + C_{\Delta\lambda} \tag{1}$$

where $C_{\Delta\lambda}$ is the absolute calibration constant of the photometric system, tied to the Earth flux of an A0-type star of magnitude $V = 0$, and $f_{\Delta\lambda}$ is the observed flux. In order to compute the expected flux of a PMS star or young BD in the pass-band $\Delta\lambda$ of a given filter we proceed as follows. We first determined the transmission curve, T_λ, that is the product of detector quantum efficiency and the filter transmission curves. We then compute:

$$f_{\Delta\lambda} = \frac{1}{A_{\Delta\lambda}} \cdot \int_{\lambda_1}^{\lambda_2} F_\lambda \cdot T_\lambda \cdot d\lambda \tag{2}$$

where

$$A_{\Delta\lambda} = \int_{\lambda_1}^{\lambda_2} T_\lambda \cdot d\lambda \tag{3}$$

and F_λ is the absolute flux of a given PMS star or young BD. For this purpose we use the synthetic low-resolution spectra for low-mass stars and BDs calculated by Allard & Hauschildt (1995) with their NextGen model-atmosphere code.

As an example of our procedure we show in Fig. 5 a NextGen spectrum with $T_{\rm eff}$=2700 K and the r', i' and z VST+OmegaCam transmission curves overplotted. However, the flux $f_{\Delta\lambda}$ that we obtain in this way is the one at the surface of the star. In order to derive the observed flux at any distance d one has to correct the flux by the factor $(R_\star/d)^2$ i.e.:

$$f_{\Delta\lambda}(d) = f_{\Delta\lambda} \cdot (\frac{R_\star}{d})^2 \tag{4}$$

where $R_\star$ is the object radius. The values for $R_\star$ can be computed from theoretical PMS evolutionary tracks which in our case are those by

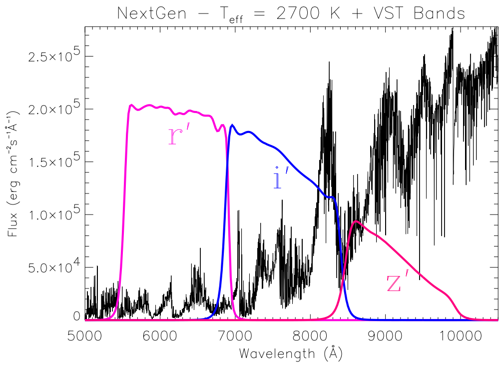

Fig. 5. Example of a young BD NextGen spectrum. The r', i' and z VST+OmegaCam transmission bands are overplotted.

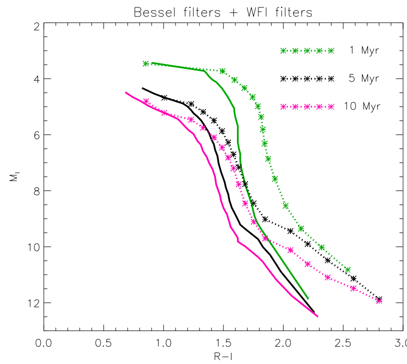

Fig. 6. Theoretical M$_I$ versus $(R - I)$ color-magnitude diagram. the 1, 5 and 10 Myr isochrones by Baraffe et al. (1998), reproduced also by us, are plotted as continuous lines. The isochrones in the WFI system are represented with dotted lines. The asterisks represent different NextGen models in the T$_{\rm eff}$ range 2500–4200 K (masses from about 0.02 to 1.20 $M_\odot$).

Baraffe et al. (1998). Finally, setting d=10 pc and using Eq. 1, one can derive absolute magnitudes for a given, T$_{\rm eff}$, age and radius and hence, determine the isochrones in the color-magnitude diagrams. In this way we were able to reproduce the isochrones for the Bessel photometric system reported by Baraffe et al. (1998).

We have also applied our procedure to determine the isochrones for the WFI+ESO 2.2m telescope system. In Fig. 6 the 1, 5 and 10 Myr isochrones by Baraffe et al. (1998) are compared with those in the WFI photometric system. Note the large differences, in particular for the coolest objects.

Finally, in Fig. 7 the Baraffe et al. (1998) isochrones are compared with those derived in the VST+OmegaCam system. As can be seen, in this case there are much smaller differences between the isochrones. This is likely due to the fact that the properties of the r', i' and z VST+OmegaCam filters are more or less similar to those of Bessel bands.

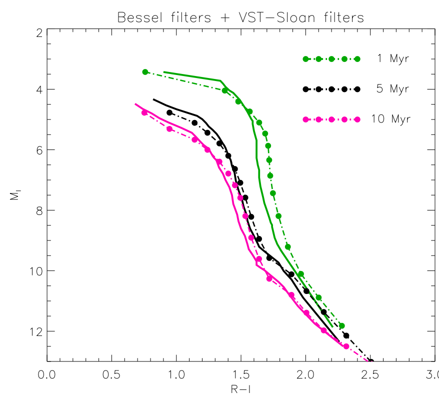

Fig. 7. Theoretical M$_I$ versus $(R - I)$ color-magnitude diagram. the 1, 5 and 10Myr isochrones by Baraffe et al. (1998) are plotted as continuous lines. The isochrones in the VST+OmegaCam system are represented with dotted lines. The dots represent different NextGen models in the T$_{\rm eff}$ range 2500–4200 K (masses from about 0.02 to 1.20 $M_\odot$).

5.2. A possible survey with VST in SFRs

With VST it will be possible to map out large sky areas fairly efficiently with relatively short exposures. In Orion, at an age of about 1–3 Myr, objects near the H-burning limit will have $(R - I) \sim 1.72$ and $I > 17$. With a 10 min. exposure with VST it will be possible to achieve a limiting magnitude of about 23 with a S/N ratio of about 16, 10 and 3 in the r', i' and z bands respectively. Considering overheads, this would allow to cover some 150 square degrees in some 20 VST nights. This would make possible the detection of many candidates to young sub-stellar objects.

With deeper exposures, it might be possible to detect planetary mass objects: in a 1.5 hour exposure, a limiting magnitude of about 25 would be achieved with a S/N of about 12, 8 and 5 in the r', i' and z bands respectively. The search for this type of objects would be much more time consuming and a compromise between the depth and the covered areas in the associations must be found.

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