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Wide-Field Imaging In Star Forming Regions: search for young brown dwarfs

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Abstract. We present strategies for the identification of low-mass Pre-Main Sequence stars, young brown dwarfs and free-floating planet candidates using wide-field imaging techniques in star forming regions. We report first results of an optical and near-IR imaging survey in southern star forming regions and multi-object spectroscopic follow-up. Future surveys with VST and VISTA will significantly increase the number of young BD candidates for IMF studies in the sub-stellar regime and will allow the search for young free-floating planets.

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

1. Introduction

An important issue for the understanding of the star and planet formation process is the Initial Mass Function (IMF). The IMF 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 below 0.1 $M_\odot$ (Hillenbrand & Carpenter 2000), in T associations like Taurus-Auriga there is indication 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 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 accreting matter (Kroupa 2001, 2002). Therefore, many low-mass protostars may never complete their accretion and hence can result as sub-stellar objects. However, other processes different than the photo-evaporation of circumstellar accretion matter may operate. For ex-

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ample, 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 ejection 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. This hypothesis has also been extrapolated to planetary mass objects. For instance, some authors (Lin et al. 1998) have proposed that the population of free-floating, very low-mass objects found in some SFRs is dominated by ejected massive "Jupiters", originally formed by agglomeration of rocky cores and subsequent gas accretion in the disk around a solar-mass star.

Therefore, in order to tackle the problem of the sub-stellar IMF it is necessary to search for the population of dispersed young BDs in star forming regions (SFRs). Wide-field imaging in the optical and near-IR is the primary tool for the selection of the candidates. Such investigation may also provide interesting candidates for giant free-floating planets (FFPs).

2. Why in Star forming regions ?

Pre-main sequence (PMS) clusters are specially suited for the study of the IMF. The easiest time to determine the IMF is early in the life of a stellar cluster or association, before high-mass stars burn out, and before dynamical friction segregates the masses and lower mass systems are ejected. At ages of a few Myr, it is easier to detect faint objects down to the hydrogen-burning limit. The use of wide-field broad-band photometry techniques in SFRs allows to identify statistically complete samples of VLM PMS stars and young Brown Dwarf (BDs) candidates.

Another important issue is that the luminosity of VLM stars and BDs is a decreasing function of age. Their bolometric luminosity, $L_{\rm VLM}$, evolves with time, t, as $L_{\rm VLM} \propto t^{-1.2}$ (Black 1980; Burrows et al. 1995). This is also illustrated in the theoretical color-magnitude diagram in Fig. 1.

Similar arguments apply to giant planets. However, since giant planets do not burn Deuterium, their luminosity decreases more rapidly with time than for BDs. A 1 Myr old jovian-mass planet may be 10.000 times more luminous than its 1Gyr old counterpart. Therefore, it may also result much easier to detect giant FFPs in SFRs, when they are very young.

Therefore, our strategy is to use color-magnitude diagrams and theoretical isochrones to preselect candidates for young BDs and FFPs in SFRs.

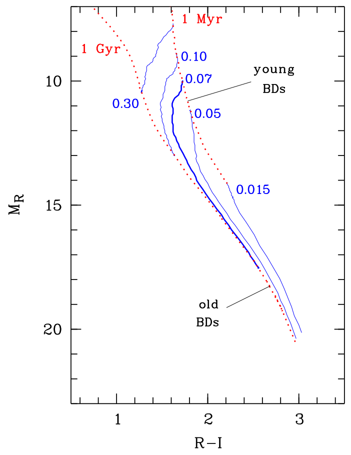

Fig. 1. Theoretical color-magnitude diagram. The isochrones (dotted lines) and PMS tracks in solar masses (continuous lines) are from Baraffe et al. (1998).

3. Wide-field imaging observations and spectroscopic follow-up

We have started a program of wide-field imaging in southern SFRs using the Wide-Field Imager (WFI) at the ESO 2.2m telescope. The observed regions include the Chamaeleon II dark cloud (about 2 sq. deg.), Lupus (about 0.5 sq. deg.), L1616 in Orion (0.5 sq. deg.) and several regions towards the TW Hya association (about 0.7 sq. deg.). The SFRs were observed in the B, V, 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. (2002).

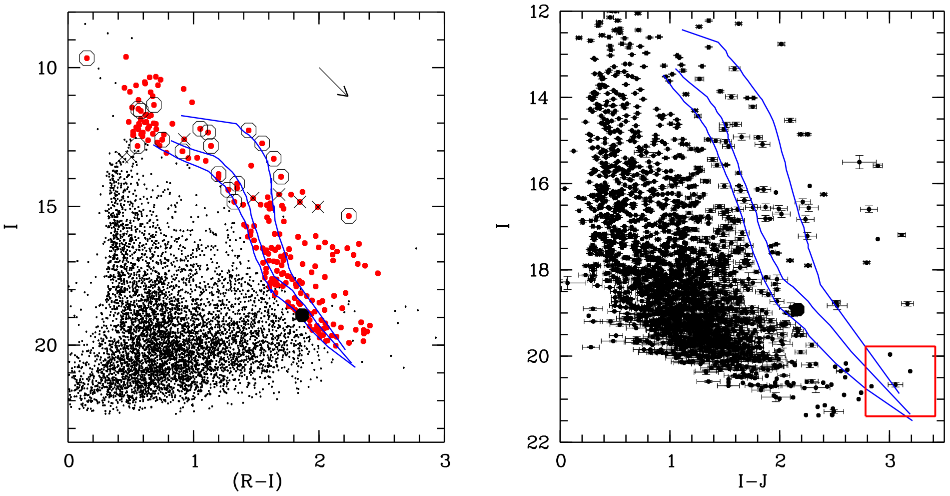

Fig. 2. Left panel: I versus $(R-I)$ diagram for the point-like objects extracted from the WFI images in L1616. The continuous lines represent the theoretical PMS isochrones by Baraffe et al. (1998) for 1, 5 and 10 Myr, respectively, shifted to a distance modulus of $8^{m}.3$ (d=450pc). X-ray sources detected with high confidence but still lacking optical spectroscopy are represented with "×" symbols. Adapted from Alcalá et al. (2004). **Right panel**: I versus $(I-J)$ diagram for the point-like sources in L1616 derived by matching the optical catalogs with those obtained from the JHK_S NTT-SOFI survey in the region. The theoretical PMS isochrones are as in the left panel. The big black dot in the bottom of each diagram represents the BD candidate, whose spectrum is shown in the lower panel of Fig. 3.

In Fig. 2 (left panel) the I vs. $R-I$ diagram of the L1616 region in Orion is shown. This example shows the technique to preselect the VLM PMS stars and BD candidates. Many PMS stars, characterized by us previously (Alcalá et al. 2004) and represented with circles in the left panel of Fig. 2, are used to define the PMS locus in the diagram. The grey dots represent objects above the 10 Myr isochrone.

In the right panel of Fig. 2 the I vs. $J-I$ diagram of objects in L1616 in Orion is shown. An interesting result is that the objects inside the lower-right square have photometric properties very similar to those of σ-Ori 47, a free-floating planetary-mass object, member of the young cluster σ-Orionis (Zapatero-Osorio et al. 2002).

We have performed a first spectroscopic follow-up of the selected candidates in L1616 using FORS2 at the VLT-UT4. Some examples of new PMS sequence stars are shown in Fig. 3. The spectrum of a BD candidate, represented with the big black dot in the color-magnitude diagrams in Fig. 2, is shown in the lower panel, while a detail of the spectrum, in the Hα-Li range, of a new VLM PMS star is shown in the middle panel. Also, the spectrum of a new, extreme ($W_{H\alpha} \approx 200$ Å) and VLM star is shown in the upper panel. So far we have identified about 15 new VLM PMS stars in L1616, but the spectroscopic follow-up will continue in this and the other SFRs selected by us using also NICS at the TNG. We expect to identify many more low-mass PMS stars and young BDs.

4. The future: VST and VISTA

The new generation of CCD mosaic cameras will allow to single out candidates to young BDs and FFPs using color-magnitude diagrams. It is expected that surveys with VST (VLT-Survey-Telescope) and VISTA (Visibile & Infrared Survey Telescope for Astronomy)

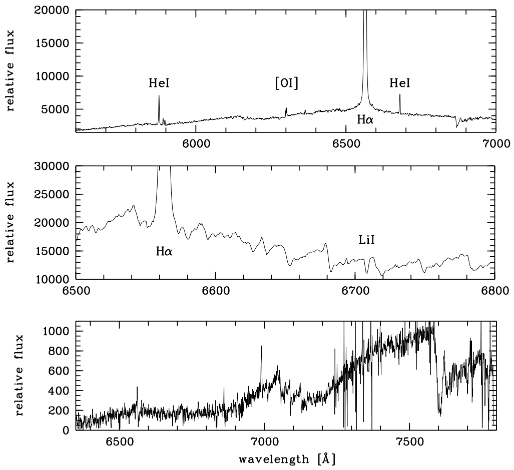

Fig. 3. Examples of FORS2 spectra.

in star forming regions will provide a wealth of data suitable for these purposes.

We foresee to perform studies with VST in the r', i', z and Hα bands in wide areas of the Orion and Sco-Cen OB associations. The main goals of this survey will be *i)* to single out young BDs and FFPs; *ii)* characterize the PMS populations in order to study the IMF down to the sub-stellar regime; *iii)* study the star formation history; *iv)* investigate the disk frequency in sub-stellar objects; *v)* study possible mass segregation effects and *vi)* investigate magnetic activity in sub-stellar objects.

With VST and VISTA it will be possible to map large sky areas very efficiently with relatively short exposures. For instance, 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, for the search of BDs. The FFPs would require deeper exposures: 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.

Considering overheads, this would allow to cover some 150 square degrees in some 20 VST nights in both OB associations. The search for FFPs 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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