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Formation and Early Evolution of Brown Dwarfs

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Abstract. We present a project aimed at constraining the mechanism of formation of Brown Dwarfs as well as disk and activity characteristics of young Brown Dwarfs in star forming regions. As part of this project we also developed an efficient spectral classification scheme for faint cool dwarfs based on very low-resolution near infrared spectroscopy, which we succesfully applied to young embedded Brown Dwarfs. We discuss in detail evidence for and properties of disks associated with a sample of brown dwarfs in the star-forming region ρ-Oph. For this sample we derive photospheric parameters from low resolution near infrared spectroscopy and model the mid-infrared excess by means of passive, flared circumstellar disks. In all cases, the mid-infrared excess is consistent with the SED expected from irradiated dusty disks. Our results suggest that disks may be commonly associated to young Brown Dwarfs and isolated planetary-mass objects. Finally, we discuss the possibility of using these and future data to discriminate between various formation scenarios for substellar objects.

Key words. Brown Dwarfs – low-resolution near-infrared spectroscopy

1. Introduction

The discovery of large numbers of sub-stellar mass objects, down to planetary masses, in regions of star formation has provoked an intense debate on the formation mechanism of such objects. Do they form, as solar mass stars do, from the collapse of a molecular core (Shu et al. 1987)? Are they stellar embryos, whose further growth is prevented by dynamical ejections from small stellar systems (Reipurth & Clarke 2001; Bate et al. 2002)? Or are they “planets” i.e., objects that form within circumstellar disks (Papaloizou & Terquem 2001; Lin et al. 1998)? Is there a single formation process for all substellar objects? What is the lowest mass for the gravitational collapse mechanism?

A crucial contribution to this debate is expected from studies of the circumstellar disks (if any) associated with sub-stellar objects, since different theories make very different predictions. Disks are a necessary step in any formation mechanism that involves accretion from a parental core. If BDs form from core collapse, they should be associated to disks similar in properties to those found around low mass pre-main–sequence stars (T Tauri stars; TTS). A prediction of the stellar embryo theory is that the disks should be truncated by the ejection mechanism, so that they should be small and short-lived. In the “planetary” hypothesis, any circumstellar disk should be even less substantial.

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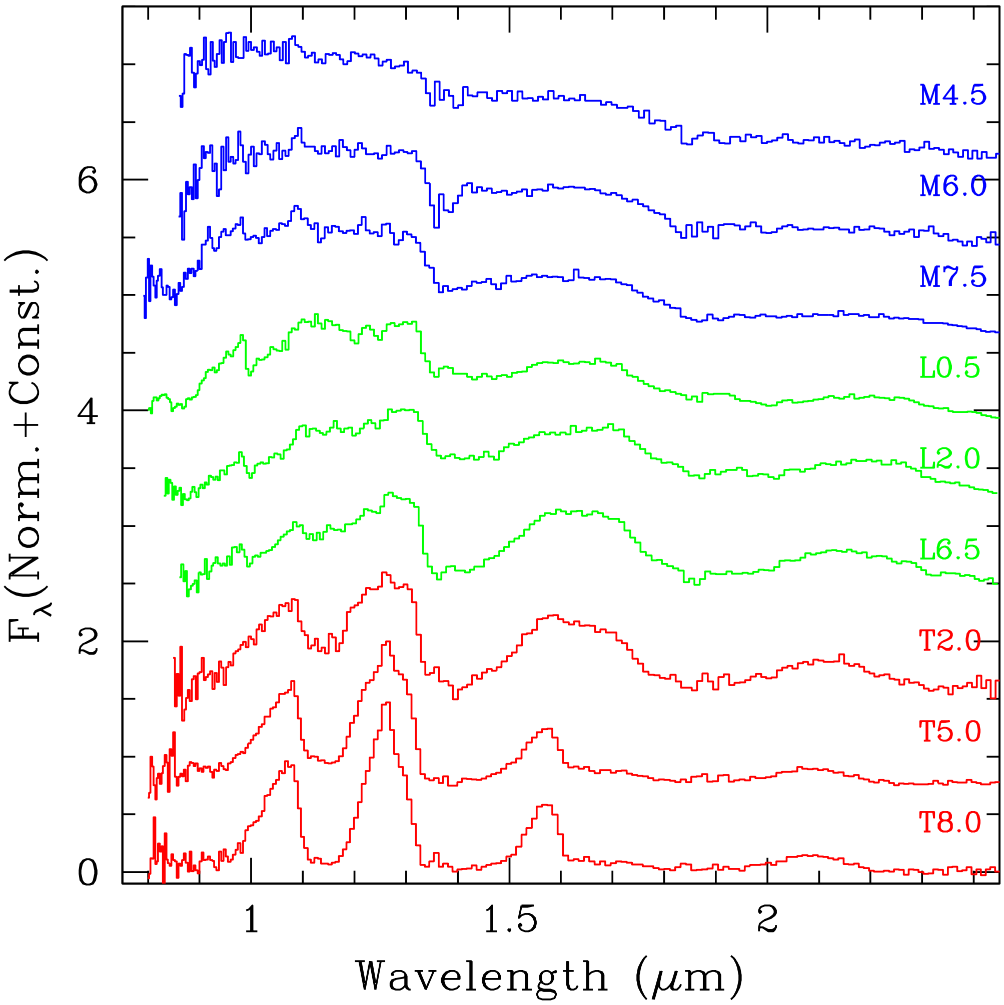

Fig. 1. Sample of field dwarfs spectra obtained for our programme, from M4.5 through T8. the most conspicuous features in the spectra are the water absorption bands and for the T-dwarfs the methane absorption bands. Depending on signal to noise and spectral type, the spectra also show blended absorption features from CO, TiO, FeH and KI. The spectra show the evolution of the various features with the spectral type, as expected.

In some young BDs, emission in excess of that due to the photosphere has been detected in the near (Muench et al. 2001; Wilking et al. 1999) and mid-infrared (Comerón et al. 1998; 2000), and has been interpreted, by analogy with TTS, as evidence for circumstellar disks. With the aim of investigating in more detail the disk hypothesis, we initiated a long term programme of observations of young candidate BDs in star forming regions with the aim of selecting spectroscopically confirmed samples of young BDs followed by a search for the presence of disks and possibly accretion activity. The goals of this effort is to provide complete samples for determining the fraction of young BDs with disks and to measure their accretion levels, these database will be eventually confronted with observations and models of more massive young stars.

In this paper we present the results of our cool dwarfs Amici spectral classification programme, its application to young BD candidates in ρ Oph, and the first results and implicaitons of disk models applied to young BDs.

2. The Amici cool dwarfs spectral classification scheme

The first phase of the project was aimed at deriving an efficient classification scheme for faint and possibly embedded cool young (sub)stellar objects. Given the faintness of the targets in the visible range of the spectrum and the high extinction expected for many of the young BD candidates, we decided to use a classification scheme based on low-resolution near-infrared spectroscopy. The availability of the highly efficient Amici device at the TNG telescope (Baffa et al. 2001; Oliva 2000) and the positive results obtained in a pilot project on field L-dwarfs (Testi et al. 2001) suggested that very low-resolution spectroscopy in the 0.8-2.4 μm range could be the most efficient method to obtain accurate spectral classification of our targets.

The L-dwarfs sample was expanded to include warmer and cooler objects, in order to cover as uniformly as possible the spectral types M-, L-, and T-dwarf from M3 to T8. All the objects selected had been previously classified in the optical or by means of medium-resolution infrared spectroscopy by other groups (Henry et al. 1994; Kirkpatrick et al. 1995; 1999; 2000; and Burgasser et al. 2002), our final sample consists of 53 field dwarfs. All the objects in our sample were observed using the 0.″5 slit and the Amici device at the TNG during several observing runs from 2001 to early 2003. The resulting effective resolving power is ~100, approximately constant over the entire spectral range (0.8–2.4 μm) covered. Each spectrum required integration times in the range 5 to 15 minutes, depending on source brightness and sky conditions. A representative sample of spectra is shown in Figure 1.

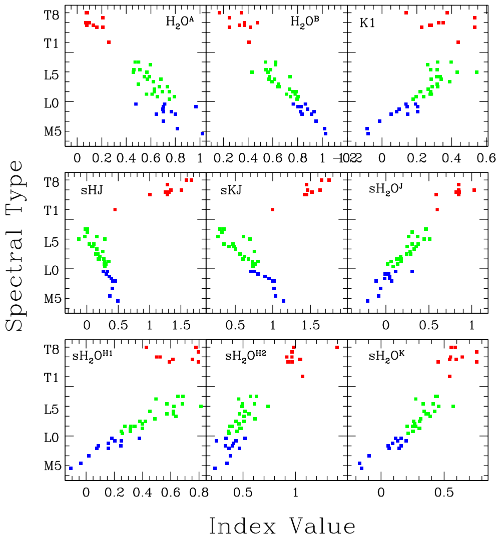

Fig. 2. Examples of spectral idices useful for spectral classification of cool dwarfs. The indices are either based on the shape/depth of the water bands or on the shape of the "residual" continuum in the J, H and K bands. It should be noted that some of the water indices become degenerate and the continuum indices show a sharp change (from "red" to "blue") for T-dwarfs, both these effects are related to the appereace of the methane absorption.

The classification method is based on the global shape of the complete low-resolution near-infrared spectra which is mainly affected by the strength and shape of the water and methane bands. Accurate classification (within one or two sub-classes) can be obtained either by means of spectral match with our library, or using selected spectral indices (Testi et al. 2001; 2002; 2003; Natta et al. 2002; see also Fig. 2).

3. The ρ Oph mid-IR excess sample

To explore the properties of BD disks, we started selecting a sample of young BD candidates with mid-infrared excess. The goal of this first study was to prove that spectroscopically confirmed young BDs have infrared excess that can be interpreted as due to disk emission. To this effect, the nine objects in our selected sample are drawn from the ISOCAM observations of the ρ Oph cloud (Bontemps et al. 2001). we selected all sources in the ISOCAM sample with visual extinction less than ~8.5 mag and luminosity less than ~0.04 L⊙ according to the Bontemps et al. (2001). The first criterion ensures the possibility of obtaining high signal to noise specta across the entire near infrared range. The low luminosity was required to increase the chance of selecting objects in the range of masses we are interested in. Some of the selected sources were known from previous studies to be very low-mass objects, likely young BDs. Hereafter we will refer to the objects using their number in the Bontemps et al. (2001) ISOCAM list.

Near-infrared spectra for the objects in our sample were acquired at the TNG using the NICS instrument and the Amici disperser. the resulting effective resolution is approximately $\Delta\lambda/\lambda \sim 100$, approximately constant across the entire spectral range (0.8–2.4 μm), as for the field dwarfs. The spectroscopic observations were complemented by Gunn-i photometry obtained at the Danish telescope on the ESO La Silla Observatory, and by J, H, and K_s photometry from 2MASS. Additional L' and R-band photometry for some of the sources were available from Comerón et al. (1998). Photospheric parameters for all the objects were derived by comparing spectra and broad band magnitudes with comparison field dwarfs and theoretical models (from Allard et al. 2001). The procedure used and the accuracy of the results are described in Testi et al. (2002) and Natta et al. (2002). All objects are found to be substellar, one of them (#33, also known as GY11) is probably below the deuterium burning limit. The position of the selected objects on the HR diagram is shown in Figure 3.

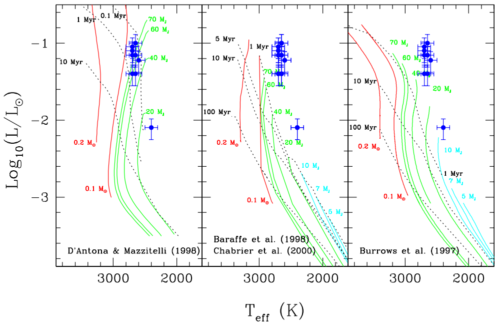

Fig. 3. Position on the HR-diagram of the objects in the ρ Oph sample. In each panel we compare the position of the objects with state of the art evolutionary tracks from the Roma, Lyon and Tucson groups. The very young ages are consistent with the age of the cluster derived from the more massive members (~0.3 Myr). With the exception of GY11 (the lowest mass member), all the object lie in a tight region of the diagram, this is a consequence of the selection criteria (see Natta et al. 2002 for details).

4. Disk models

For each system we computed the SED predicted by disk+photophere models, assuming that the disk is heated by the radiation of the central object. To compute the disk emission we follow the formalism of Chiang & Goldreich (1997), with some improvements and modifications. The disk is in hydrostatic equilibrium in the vertical direction (flared), and, at each radius, the vertical temperature structure of the disk is described in terms of two components: the disk surface, optically thin to the stellar radiation, and the disk midplane. Such disk is a scaled-down version of TTS typical disks. It extends inward to the stellar radius, and outward to $R_D=1 \times 10^{15}$ cm (67 AU). The total mass is $M_D \sim 0.03\ M_\star$, and the surface density varies as R^{-1}. The dust in the disk midplane has opacity $\kappa = 0.01(\lambda/1.3\text{mm})^{-1}$ cm^2 g^{-1}. The results of the model calculations are shown in Fig. 4.

As pointed out in Natta & Testi (2001), most of the disk parameters are irrelevant for the calculation of the mid-infrared disk emission,or appear in combinations, and cannot be determined individually. As long as the disk midplane remains optically thick to mid-infrared radiation, the only parameters that affect the SED in the near and mid-infrared are the geometrical shape of the disk (i.e., the flaring angle), the inclination to the line of sight and, to some degree, the disk inner radius R_i.

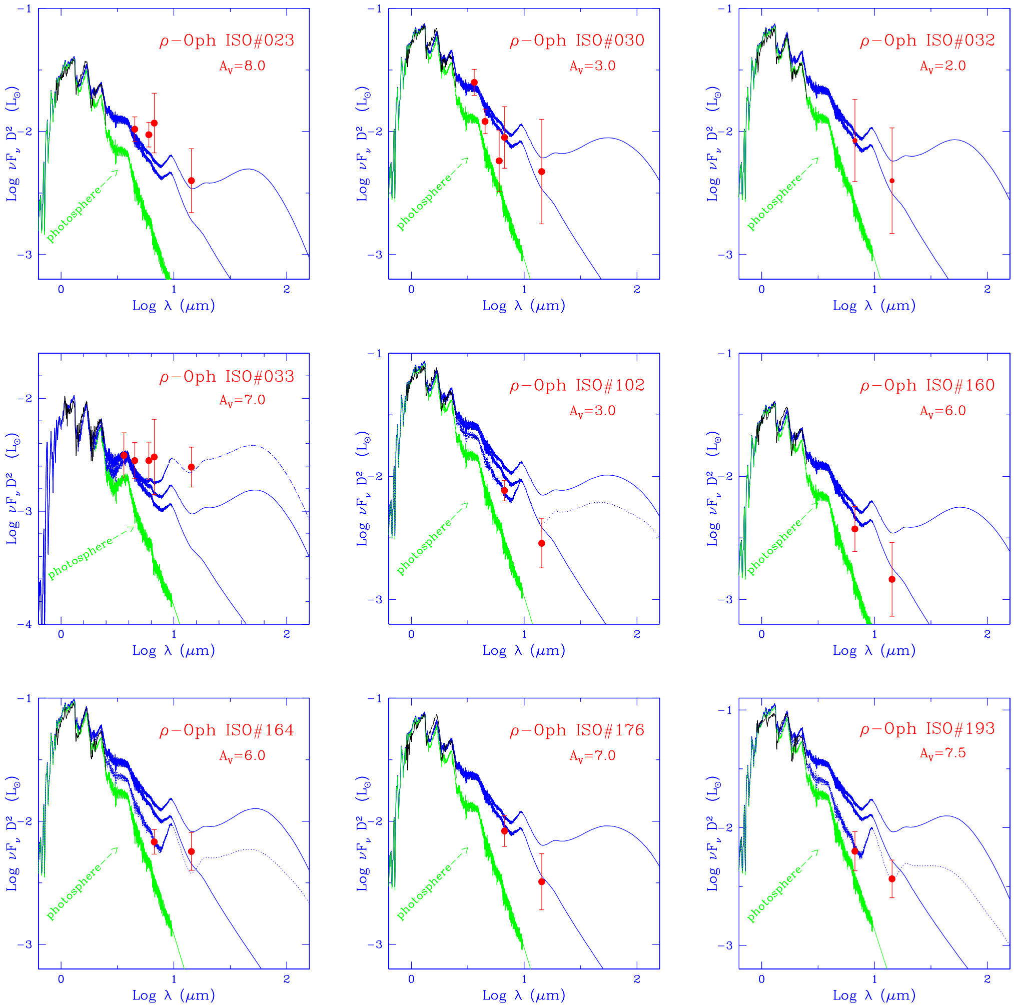

Fig. 4. Comparison between observed points and computed disk and photosphere spectral energy distributions. The green jagged line shows the SED of the photosphere. The combined SED of the photosphere plus disk is shown by blue lines; in each panel, the two solid curves refer to face-on flared (upper curve) and flat disks (lower curve), with R_i=$R_\star$. For #033, the dot-dashed curve shows the SED of a face-on, flared disk with R_i=3$R_\star$. Finally, we show on three panels the SEDs of tilted flared disks (dotted lines), seen by the observer with inclinations of69^o (#102), 80^o (#164) and 86^o (#193) respectively (0^o for face-on disks).

There is also some dependence of the shape of the SED on the surface dust model; however, since the luminosity intercepted and reradiated by the optically thin surface layers is fixed, variations due to (reasonable) changes of the grain properties are well within the uncertainty of the existing observations.

All flared disk models have strong strong silicate emission at 10 μm and a rather flat spectral slope between the two ISO bands at 6.7 and 14.3 μm. If, rather than extending all the way to the stellar surface the disk is truncated further out, as predicted by magnetospheric accretion models in TTS, at each radius the surface of a flared disk intercepts and reprocesses a larger fraction of the stellar radiation. The disk emission increases correspondingly at all wavelengths but in the near-infrared, where one is sensitive to the lack of the hottest disk dust. A model with $R_i \sim 3R_\star$ may account for the large observed mid-infrared excess of #033, as discussed in Testi et al (2002). Large variations of the predicted SED occur if the disk shape changes. Geometrically thin, "flat" disks, i.e., disks where the grains are not well mixed with the gas, but have collapsed onto the disk midplane predict a much lower mid-infrared emission and a SED close to a power law $\nu F_\nu \propto \nu^{4/3}$ (see also Apai et al. 2002).

5. Implications

The comparison of the ISO observations to the model predictions shows that irradiated disk models can account for the observed mid-infrared excess. More precisely, and in spite of the large uncertainties of the ISO data, the computations of Natta et al. (2002) show that there are five systems out of nine (#030, #032, #102, #160, #176) are extremely well fit by flat disk models. Two objects (#023 and #033) seem to require flared, face-on disks, while two others have a lower mid-infrared excess, consistent with disks seen rather edge-on. However, given the large error bars and the model uncertainties, most objects with flat disks are also consistent with flared disk models with large inclination, as shown for the case of #102.

This comparison between models and observations proves that the mid-infrared excess associated to many young BDs can be accounted for by the emission of circumstellar disks heated by the radiation of the central object. Few disk properties, however, are convincingly constrained by existing observations, and we do not want to overinterpret our results, given the large uncertainties of the observed fluxes, and the simplicity of the adopted models. However, in our limited sample of nine stars we find disks of different flavours, and, in particular, an indication that many BDs may have flat disks. If we consider also the three objects in Cha I studied in Natta & Testi (2001) we have three objects with clear evidence of flared disks, and nine where flat disks seem more appropriate, although we cannot rule out almost edge-on flared disks for some of them. This is potentially an interesting result, since it seems natural to associate flat disks with dust sedimentation toward the midplane. In our selection of ISO sources, we have an obvious strong bias against objects with flat disks, since we required that the sources were detected by ISO in both bands. So, the fact that our objects with the lowest 6.7 μm fluxes (Cha Hα1 and #033) have flared disks is not surprising. However, there is no bias against selecting flared disk objects of higher luminosity, and we find only one (#023). The possibility of dust settling in these very young low-mass objects is intriguing. However, it needs to be confirmed by high-quality photometric observations at longer wavelengths, before entering into further speculations.

The ejected embryos hypothesis does not exclude that BDs may have a small, and therefore short-lived, circumstellar disk. Estimates by Bate et al. (2002) give disk radii of about 20 AU or less. The existing infrared data do not allow us to rule out such possibility, since the SED of a model with R_D=20 AU will differ from the SED of a disk with R_D=75 AU only at wavelengths $\geq 40\,\mu$m. The mass of the disk is not predicted by existing calculation, nor constrained by the observations, since the only constraint we can set is that the disk has to be optically thick in the mid-infrared. This, however, only requires a disk mass of 10^{-5}–10^{-6} $M_\odot$ (or M_D/Mstar$\sim$ 10^{-4}), which is still consistent with a typical disk (having M_D/Mstar$\sim$ 0.03, R_D=75 AU), truncated at R_D=20 AU. Until far-infrared and millimeter data become available, the only way to validate these models is to determine the fraction of disks in unbiased samples of BDs of known age.

In all objects, the mid-infrared excess is consistent with the predictions of disks irradiated by the central object. We find no evidence of strong accretion occurring in these systems, based on the fact the observed near-infrared fluxes are dominated by the emission of the photospheres, and there is very little contribution (if any) from hot dust. However, it is not clear to which degree the near-infrared excess in very low-luminosity objects is a sensitive indicator of accretion (see, for an example of an actively accreting object with no near-infrared excess, Fernández & Comerón 2001), and this issue should be explored more quantitatively in the future.

We want to emphasize that our results do not discriminate yet between different formation mechanisms, namely between the possibility that BDs form from the gravitational collapse of individual, very low-mass cores, and the ejected embryo theory. We fit the observed mid-infrared excess with a scaled-down version of disks around the more massive TTS. This, however, just implies that "normal" disks can account for the existing observations, since few parameters are actually constrained. Only observations at longer wavelengths can measure the disk radius and mass, since the lower limits that we can derive from the conditions that the disk is optically thick in the mid-infrared are hardly significant.

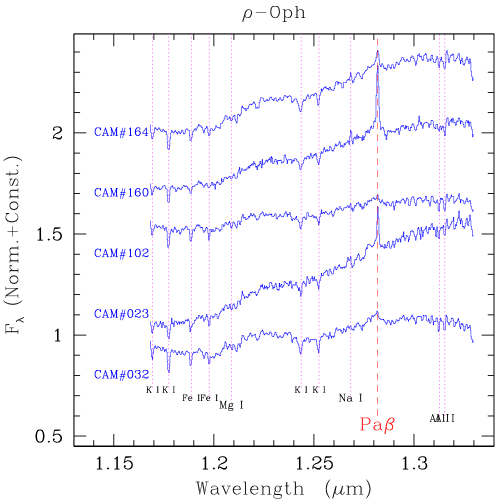

Fig. 5. Examples of VLT/ISAAC J-band spectra of spectroscopically confirmed young BDs with infrared excess. All spectra show Paβ emission, at different levels, indicating a strong activity, probably due to accretion. Several photospheric absorption lines are also visible.

6. How to constrain BDs formation theories

It is clear that the next step, in oder to constrain the formation mechanism of BDs, is to study the disk accretion properties and the disk statistics in large samples of spectroscopically confirmed young BDs. We are currently engaged in both type of programmes using the the ESO telescopes NTT/SofI and 2.2/WFI for imaging surveys, the TNG/Amici for spectral classification of the candidate young BDs, and the VLT to search for L-band excess and infrared/optical emission lines. In Figure 5 we show a sample of preliminary ISAAC spectra which reveal a strong Paβ emission line, probably related to accretion activity. These and other preliminary results suggest that young BDs undergo a similar phase as the more massive T Tauri stars, strongly suggesting a similar formation mechanism.

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