Brown Dwarfs
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Brown Dwarfs in Southern Star Forming Regions

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Abstract. Most of the star forming regions within 200 pc from the Sun are located South of the celestial equator. Brown dwarfs or strong candidates have been discovered in all of them, and have been often studied at multiple wavelenghts. This paper summarizes some highlights of the research on young brown dwarfs in these regions.

1. Introduction

Why concentrating our attention in the Southern hemisphere when dealing with young brown dwarfs? The Taurus clouds and the Orion complex are gold mines of information on star formation down to substellar masses, and contain enough objects and unanswered questions to keep observers busy for many decades to come. The moderately Northern declination of Taurus and the equatorial location of Orion provide easy accessibility to observers in the North where state-of-the-art facilities have been traditionally located.

However, the Northern hemisphere is not where most of the star forming activity in our galactic neighbourhood is taking place. In the foreword of a proceedings book on Southern star forming regions published over ten years ago (Reipurth 1991) its purpose is declared as:

"...to attract attention to the richness of southern star forming regions. Four out of five of the nearest star forming cloud complexes are in the southern sky, and yet, for geographical reasons, most of the observational work on the formation of stars has been performed in the northern sky. With the growth in the number of large southern [facilities]... the situation is fortunately improving."

This remains valid today. New ground-based facilities, like the VLT, Gemini, ATCA, and SEST have placed Southern instruments at the level and sometimes ahead of their Northern counterparts, and planned facilities like APEX and ALMA will make possible studies of Southern star forming regions to a level of detail unavailable from the North. Large-area or all-sky surveys from the ground, like 2MASS or DENIS, have provided valuable databases for star formation studies penetrating the brown dwarf regime. Space-based facilities like HST, ROSAT, ISO, Chandra and XMM have contributed to effectively erase the distinction between Northern and Southern regions, a trend that will continue with SIRTF, Herschel, or NGST. On the other hand, most star forming regions are indeed in the Southern hemisphere. The list of the most important regions within 200 pc from the Sun includes four Southern ones (Chamaeleon, Lupus, ρ Ophiuchi, R Corona Australis) versus only Taurus in the North. The score favors the South even more if we include the Southern Coalsack, a rare nearby star forming site where we can study star formation *before* it has begun, and recent additions such as TW Hya, η Cha, and other smaller groups (Hoff et al. 1998, Mamajek et al. 1999, Li et al. 2000, Jayawardhana & Brandecker 2001).

2. Diversity

Most current topics of interest in young brown dwarf research need statistically significant samples formed in a variety of environments. A review of topics covered in this conference testifies to this: the mass function and its possible cutoff, the formation mechanisms (isolation vs. ejection) of brown dwarfs, the verification of evolutionary tracks, the influence of the environment, the existence, distribution and implications of the circumstellar material, the origin and evolution of chromospheric activity, the abundance and parameter space of multiplicity, the evolution of rotation, or the impact of accretion. Many of these issues can only be answered if many star forming regions with widely different characteristics are observed in detail. In this regard, Taurus and Orion are important but not sufficient.

Southern star forming regions provide much of the diversity needed. Among the largest regions we find masses ranging from $(2-4)\times10^4$ $M_\odot$ in ρ Oph and Lupus to $(3-10)\times10^3$ $M_\odot$ in Chamaeleon or R CrA (Dame et al. 1987). Crowding in the densest regions displays an even wider range, from over 10,000 stars pc^{-3} in ρ Oph, to 500-2,000 in Chamaeleon, Lupus 3 and R CrA (Oasa et al. 1999, Nakajima et al. 2000, Wilking et al. 1997), to zero or nearly in the Coalsack (Tachihara et al. 2002). Also the star forming environment presents potentially important differences: Lupus, ρ Oph and the Coalsack belong to the Scorpius-Centaurus OB association (Blaauw 1991) and their history may have been influenced by the energetic output of nearby massive early-type stars (Tachihara et al. 2002). On the other hand, R CrA and Chamaeleon are more isolated and thus more Taurus-like in representing a mode of undisturbed star formation.

2.1. ρ Ophiuchi

The clouds near ρ Ophiuchi mark the northern edge of the Scorpius-Centaurus association and have been one of the favorite targets of observations at all wavelengths. Most studies have concentrated on the deeply embedded (A_V up to $\simeq 50-100$ mag) Pleiades-like cluster at the core of the complex (Wilking & Lada 1983), but the extended low-mass population pervading the entire region has been sampled down to very low masses (Barsony et al. 1997). Some of the first likely young brown dwarfs were identified in ρ Oph (Rieke & Rieke 1990, Greene & Young 1992, Comerón et al. 1993), including GY 11, first noted as a possible brown dwarf by Rieke & Rieke (1990). This has been supported by subsequent studies, making GY 11 the first identified brown dwarf candidate whose status as such has survived until now. Recent estimates suggest a mass between 8 and 12 $M_{\rm Jup}$ (Testi et al. 2002), an age below 1 Myr, and a considerable mid-infrared excess (Comerón et al. 1993, 1998) that is well modelled by a T Tauri-like circumstellar disk (Testi et al 2002). Another well-studied object in the region is GY 141, also first identified by Rieke & Rieke (1990) but initially dismissed as a likely foreground object. However, its detection by ISOCAM

(Comerón et al. 1998) prompted detailed observations by Luhman et al. (1997) confirming it as a member of ρ Ophiuchi. Its M8.5 spectral type and the detection of lithium in its mid-resolution spectrum (Martín et al. 1999) establish it as a young brown dwarf. Evidence for circumstellar emission at mid-infrared wavelengths among brown dwarf candidates in ρ Oph and other star forming regions has been found by ISOCAM to be a ubiquitous feature and an efficient method of selecting young low-mass objects (Comerón et al. 1998, Bontemps et al. 2001).

The identification of low mass stars in ρ Oph by their X ray emission dates back to the early observations by the Einstein satellite (Montmerle et al. 1983). They were greatly improved by ROSAT (Casanova et al. 1995, Grosso et al. 2000) and more recently by Chandra, which has detected some of the brown dwarfs identified at other wavelengths, including GY 141 (Imanishi et al. 2001). On the other side of the spectrum, searches for millimeter emission from heated dust in circumstellar envelopes have been carried out by André & Montmerle (1994) and Motte et al. (1998) on samples including brown dwarfs. The non-detection of the latter may be due to insufficient sensitivity of current instrumentation (Testi et al. 2002). This may change when millimeter and submillimeter facilities like APEX and ALMA become a reality.

3. Chamaeleon

The Chamaeleon star forming region encompasses three complexes consisting of mostly sparsely populated clouds (Schwartz 1991). The X-ray emitting stellar population reveals a widespread distribution of low mass stars (Alcalá et al. 1995, 1997) extending beyond the clouds' boundaries. ROSAT pointed observations with integration times of several tens of ksec were able to detect very late-type objects that at the age of the Chamaeleon complex (~ 2 Myr; Comerón et al. 2000) can be classified as *bona-fide* brown dwarfs, thus providing the first evidence that brown dwarfs are also X-ray emitters (Neuhäuser & Comerón 1998, Neuhäuser et al. 1999).

Wide area searches for brown dwarfs in Chamaeleon have used techniques such as near-infrared excess (Cambrésy et al. 1998, Oasa et al. 1999), mid-infrared excess (Persi et al. 2000), near-infrared variability (Carpenter et al. 2002), or narrow-band photometry on particular spectral features (Lopez Martí and Eislöffel, 2001). All such techniques are affected to some degree by contamination by unrelated sources or inaccuracies in the determination of physical parameters, and follow-up programs are under way to obtain follow-up spectroscopy for a more robust determination of properties. A serious issue remains however in the different and often poorly characterized selection effects affecting all these techniques and the subsequent difficulties in evaluating completeness corrections.

Several brown dwarfs in the central region of the Chamaeleon I cloud near HD 97048, with spectral types ranging from M6 to M8 and Hα emission (Fig. 1) have been observed in detail following their discovery by Comerón et al. (1999, 2000). High resolution spectroscopy searching for radial velocity variations due to close companions has been reported by Joergens & Guenther (2001; see also Joergens' paper in this volume). Neuhäuser et al. (2002) have searched for

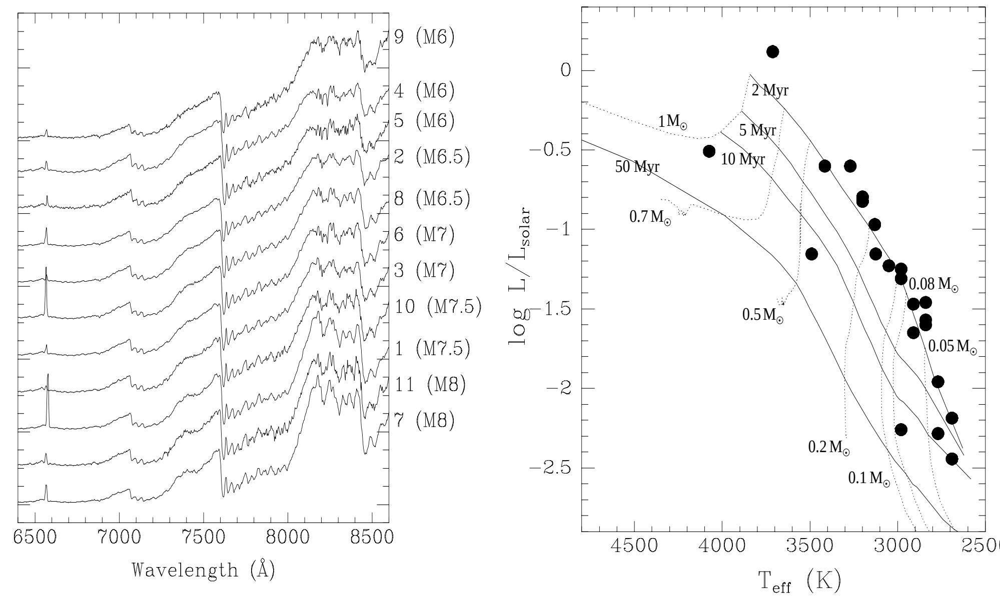

Figure 1. Spectra of late-type M objects (left) identified in the central region of the Chamaeleon I cloud. The temperature-luminosity diagram (right) shows the position of all the members identified in the same area, including higher mass objects, superimposed on evolutionary tracks by Baraffe et al. (1998). Adapted from Comerón et al. (2000).

wide companions, and mid-infrared observations showing evidence for disks has been published by Testi and Natta (2001) and Apai et al. (2002). The sample of spectroscopically identified brown dwarfs in Chamaeleon I reaches down to masses of ~ 0.03 M$_\odot$ (Comerón et al. 2000), but the abundance of very low mass objects in this region, the low extinction, the moderately high density of objects, and the proximity to the Sun make it an attractive target for deep surveys searching for Jupiter-mass objects. A first attempt in this direction by Comerón and Claes (in prep.) using ISAAC at the VLT has indeed revealed a faint object with $H = 22.0$ whose JHK colors are similar to those of early T dwarfs and whose H-band spectrum clearly shows a continuum, thus discarding emission lines as the cause for the exotic colors.

4. Lupus

The Lupus complex resembles Chamaeleon I in consisting of four major concentrations of molecular gas (Tachihara et al. 1996, 2001) over a large area of the sky, with large variations of the star forming activity among them. The often used distance of $\sim$ 140 pc (e.g. Hughes et al. 1994) placed Lupus as possibly the most nearby major star forming region. This distance has been

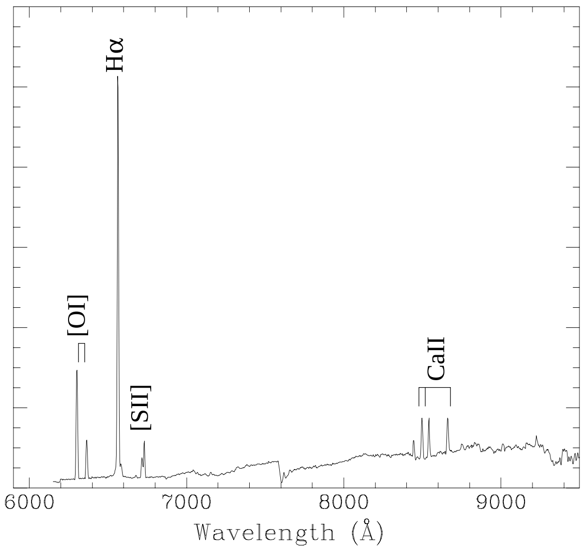

Figure 2. The spectrum of Par-Lup3-4, showing the strong emission lines on a faint, mid M-type continuum. Adapted from Comerón et al. (2002)

called into question by the parallaxes determined by Hipparcos to some of its members (Wichmann et al. 1997), which suggest a distance close to $\sim$ 200 pc or even greater (see discussion in Comerón et al. 2002). The difference of nearly one magnitude in distance modulus between the traditionally adopted distance to Lupus and the Hipparcos one translates into a factor greater than 2 in the luminosity of its members, implying a corresponding uncertainty in the intrinsic properties derived from the fit to evolutionary models, especially concerning the age.

The few specific studies on brown dwarfs in Lupus existing to date have focused on the aggregate around the Herbig Ae/Be stars HR 5999 and HR 6000 in Lupus 3. Nakajima et al. (2000) have identified faint objects with infrared excess that could be low mass brown dwarfs surrounded by hot dust. It is intriguing however how such low mass and cold objects could be surrounded by dust hot enough to emit significantly in the K band. New observations of Lupus 3 by Comerón et al. (2002) may give a hint on some singularities of these objects: one of the faint infrared excess sources of Nakajima et al. is independently identified due to its outstanding emission at Hα and other lines in the visible spectrum, in particular forbidden lines due to [OII] and [SII] (Fig. 2). Comerón et al. suggest that this object, denominated Par-Lup3-4, may be undergoing a strong burst of mass accretion. Another intriguing aspect of this object is its faintness given its spectral type (M5), a characteristic that is further discussed below in relation to a similar object discovered in R CrA.

An interesting difference between Lupus and other low mass star forming complexes is the overabundance of M-type as compared to earlier-type members (Hughes et al. 1994, Wichmann et al. 1997). The discovery of several additional faint possible members by Nakajima et al. (2000) and an additional M7.5 brown dwarf by Comerón et al. (2002) within an area of $\sim$ 100 sq. arcmin of HR 5999/6000 supports this trend that may indicate genuine differences in the mass function. It also suggests Lupus 3 as a very promising target for searches of young brown dwarfs with spectral types later than M.

5. R Coronae Australis

R CrA is another large complex at $\sim$ 150 pc from the Sun with extended clouds associated with a large, sparse low mass population identified by ROSAT (Neuhäuser et al. 2000) and an active star forming site dominated by TY RCrA, S CrA, and R CrA itself. The presence of these intermediate mass stars near the main molecular concentration resembles the centers Chamaeleon I and Lupus 3, but R CrA has more signposts of star forming activity including some bright, deeply embedded stars and several Herbig-Haro objects (Graham 1991).

A moderately dense embedded cluster of low mass stars, the Coronet, was discovered by Taylor & Storey (1984) and investigated in more detail by Wilking et al. (1997), who identified five brown dwarf candidates. However, no detailed studies of individual members are available to date. Fernández and Comerón (2001) have surveyed the region in search for faint emission-line objects, finding one with characteristics strikingly similar to those of Par-Lup3-4, described above. A strong emission line spectrum very similar to that displayed in Fig. 2 is superimposed on a M6.5 continuum.

Both Par-Lup3-4 and LS-RCrA 1 have Hα equivalent widths near or above 400 Å and are remarkably underluminous for the age and distance inferred from their membership in star forming regions, suggesting that both facts may be related. A possible explanation compatible with both objects having normal properties may be assuming that they are both surrounded by edge-on disks that are losing mass through winds, so that the emission-line spectrum produced in the disk wind is seen unobstructed while the disk blocks the light of the central source, seen only via scattered light. Some stars whose edge-on disks have been confirmed, like HH30 (Cohen & Jones 1987) and HV Tau C (Monin & Bouvier 2000), have indeed strong emission spectra with line ratios similar to those of outflows. This is not the case however neither for Par-Lup3-4 or for LS-RCrA 1, for which the intensity of Hα relative to the forbidden lines is well above that of the highest excitation outflows, indicating that the emission in the Hα line actually comes from the base of accretion columns near the surface of the object. Since the Hα emitting region should therefore be similarly blocked by an edge-on disk, the high intensity of Hα over the underlying continuum must be a real feature rather than the result of a special viewing geometry. Other late-type objects with both strong Hα emission, forbidden lines, and low luminosity are known: for example, LkHα 263C (Jayawardhana et al. 2002) is a directly confirmed edge-on disk, and the same explanation has been proposed for ITG 33A (Martín 2000). However, the Hα equivalent widths of all these objects is below 100 Å. No late-type objects with normal luminosities and Hα equivalent widths in the range of several hundred Å are known, suggesting that underluminosity may also arise as a result of the external appearance being strongly modified by evolution and not only of the existence of edge-on disks. The fact that all four objects in the Lupus 3 area examined by Comerón et al. (2002) having Hα equivalent widths in excess of 100 Å do display underluminosity to some degree supports this view. The trends observed in these objects have been qualitatively predicted by models of pre-main sequence evolution (Hartmann et al. 1997), but an extension of existing models to higher accretion rates and lower masses of the central objects are needed to understand if accretion alone can modify the observable characteristics to the extent suggested by observations.

The possibility that strongly accretion very low mass stars and brown dwarfs are systematically fainter than non-accreting ones raises intriguing questions: how common are these objects? Do they represent a common phase in the evolution of all or most very low mass stars or brown dwarfs? How long do the effects of strong accretion last in their observable features? May there exist a "hidden" population of faint, accreting brown dwarfs in star forming regions? Such questions are relevant both to observational efforts aiming at producing complete, mass-limited samples of young brown dwarfs and to future generations of theoretical models aiming at reproducing early evolution of very low mass objects taking into account the effects of accretion.

6. Concluding remarks

Current and planned astronomical instrumentation in different wavelength domains, both ground- and space-based, will enable the selection and follow-up of large samples of young brown dwarfs in all the nearby star forming regions. We may thus expect that detailed studies on brown dwarfs, now generally available only for selected objects in a few reduced areas of each star forming complex, will be extended to the whole brown dwarf contents of each region. This will enable comparative studies on intrinsic differences among regions over the whole stellar and substellar range, and ascertain whether the diversity found among global properties involve also a diversity in their brown dwarf contents. Regardless of whether or not this turns out to be so, the first glimpses on the very early stages of brown dwarfs have already revealed enough interesting features to lead to the expectation of new surprises as more detailed observations become available. The Southern regions mentioned here, and other young aggregates in the solar neighbourhood, will be important quarries for such discoveries.

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