Substellar objects in star formation regions: A deep near infrared study in the Serpens cloud^{★,★★}

A. Klotz¹, E. Caux¹, J.-L. Monin^{2,3}, and N. Lodieu⁴

¹ CESR CNRS-UPS, BP 4346, 31028 – Toulouse Cedex 04, France

e-mail: klotz@cesr.fr

² Laboratoire d'Astrophysique, Observatoire de Grenoble – BP 53, 38041 Grenoble Cedex 09, France

³ Institut Universitaire de France

⁴ Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany

Received 14 April 2004 / Accepted 6 May 2004

Abstract. We present near infrared (J , H and K_s) observations of a $5' \times 10'$ sample field in the Serpens Star Formation region obtained with SOFI at the NTT. These observations are sensitive enough to detect a $20 M_{\text{Jup}}$ brown dwarf through an extinction of $A_V \sim 16$ and are used to build an infrared census of this field in the cluster. From photometry and mass-luminosity models, we have developed a detailed methodology to extract quantitative parameters (distance modulus, extinction, spectral type, masses) for objects observed towards and inside the Serpens molecular cloud. An extinction map of the region is derived allowing us to disentangle cloud members from background field objects. Luminosities and masses for 14 low-mass stars and substellar object candidate members of the cluster are derived. Three of these objects have masses compatible with the brown dwarf regime and one of them (BD-Ser 1) was observed spectroscopically with ISAAC at the VLT, confirming its substellar status. Long-term photometric variability of BD-Ser 1 could be consistent with signs of accretion.

Key words. stars: low-mass, brown dwarfs – ISM: clouds – ISM: individual objects: Serpens molecular cloud

1. Introduction

Since the discovery of the first confirmed brown dwarfs (Nakajima et al. 1995; Rebolo et al. 1995), the interest in very low mass stars and substellar elements of the mass function has increased. Neither hot nor massive enough to ignite hydrogen in their core, brown dwarfs have masses ranging from $13 M_{\text{Jup}}$ up to $75 M_{\text{Jup}}$ (these limits change slightly with the metallicity). Neither stars nor planets, these objects contract gravitationally along the Hayashi tracks for so long that they never reach the main sequence.

Such objects have been found in the solar neighbourhood, using all-sky surveys including DENIS (Delfosse et al. 1997, 1999), 2MASS (Kirkpatrick et al. 1999, 2001; Burgasser et al. 2002); and SDSS (Hawley et al. 2002), leading to the definition of two new spectral types, L and T. One disadvantage of this wide field method within the framework of star formation

studies is that nearby very low mass stars and brown dwarfs generally happen to be quite old (age ≥ 500 Myr).

In order to reach younger objects, other authors have performed deep surveys in somewhat young open clusters including NGC 2516 (Jeffries et al. 1997), the Pleiades (Bouvier et al. 1998; Moraux et al. 2003), Praesepe (Hodgkin et al. 1999), M 35 (Barrado et al. 2001a), IC 2391 (Barrado et al. 2001b), and Alpha Persei (Barrado et al. 2002). In this case, the distance and the age of the newly found substellar objects can be readily estimated from the whole cluster ones.

Other surveys have been conducted in star-forming regions including the Trapezium Cluster (Hillenbrand & Carpenter 2000; Lucas & Roche 2000; Muench et al. 2001), Chamaeleon I (Comerón et al. 2000), ρ Ophiucus (Bontemps et al. 2001), σ Orionis (Béjar et al. 2001), Taurus (Martín et al. 2001) and IC 348 (Preibisch & Zinnecker 2001; Muench et al. 2003). In such star forming regions, one should expect the results to be closer to the “initial” part of the Initial Mass Function (IMF). Moreover, brown dwarfs can be up to two orders of magnitude brighter when younger: Baraffe et al. (1998) find that a $50 M_{\text{Jup}}$ object absolute magnitude shrinks from $K = 6.70$ to $K = 9.48$ ($L = 10^{-2} L_{\odot}$ to $L = 6 \times 10^{-4} L_{\odot}$), when aging from 1 Myr to 100 Myr.

One drawback of this method comes from the possible high absorption encountered in front of the potential candidates.

* Based on observations collected with TBL/MOICAM instrument at the Pic du Midi Observatory, France, and NTT/SOFI & VLT/ISAAC instruments at the European Southern Observatories, La Silla and Paranal, Chile (ESO Programs P63.L-0227 and P65.L-0637).

** Photometric data are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/425/927>

As soon as the visual extinction reaches $A_V \geq 10$, most of the brown dwarfs out of reach in the visible range even the current most powerful telescopes. However, the search can be pursued in the near infrared: at a distance of a few hundred parsecs and with A_V up to 30, K magnitudes of about 18 are required to probe the substellar domain. The depth of such a survey is possible using current near-infrared instruments, and large field devices are currently being built. Indeed, the identification of a significant number of young substellar (“PMS”) objects in star-forming regions will provide hints to fundamental questions relative to star formation: how is the brown dwarf formation process related to that of solar type stars? How does the spatial distribution of objects in a cloud depend on mass? Is the IMF universal? Does it keep rising in the substellar regime?

We used a photometric method (described Sect. 3) which led to the discovery of the first young brown dwarf deeply embedded in the Serpens cloud (Lodieu et al. 2002, hereafter LCMK02). This paper is a complete report on the results from a deep near-infrared (J , H , and Ks) photometric survey of a $5' \times 10'$ region in the Serpens cloud conducted with the NTT/SOFI camera in July 1999.

Section 2 presents the photometric and spectroscopic observations and the results. Section 3 details the method used to produce an extinction map of the observed region and to disentangle cloud members from background objects, using the photometric data. Section 4 discusses the properties of the low mass and brown dwarf candidate members of the Serpens cloud.

2. Observations and results

In the Serpens Cauda constellation, the Serpens cloud is one of the nearest star-forming regions, at a distance of 259 ± 37 pc (Straizys et al. 1996), 24 pc above the galactic plane. Visible images of the cloud from the Palomar Observatory Sky Survey show a large filamentary dark patch of about one degree along its largest extension. A bipolar nebula is found on the SVS76 Ser 2 (SVS2) infrared source (Strom et al. 1976) and is usually considered as the core of the cloud. Radio observations (Davis et al. 1999) show bright sources believed to be protostellar cores with polar jets, yielding even more clues to the youth of the environment. Near infrared images (Kaas 1999 – hereafter K99) show a bright diffuse nebula of about $2' \times 3'$ around the core. Many NIR photometric studies (Eiroa & Casali 1992 – hereafter EC92; Casali et al. 1993; Sogawa et al. 1997; Giovannetti et al. 1998 – hereafter GCNM98, and K99) identified young stellar objects in a radius of about $10'$ centered on the core. All these properties make the Serpens cloud a star forming region well suited to reveal pre-main sequence low-mass objects and young brown dwarf even those deeply embedded.

However, the completeness limit of these previous NIR surveys was limited to $K = 15$. The visual extinction, derived from these studies, is estimated to be higher than 10 in the central regions within a radius of $5'$ from the core and between 5 to 10 up to a radius of $10'$. From the analysis of the K -band luminosity function of the central part of the cloud, GCNM98 estimated that two bursts of star formation have occurred: a central

Table 1. Log of the NTT/SOFI photometric observations performed on July 25–27, 1999, in J , H , and Ks SOFI filters, for each of the 2 fields observed.

Band	Seeing ($''$)	Exp. time (s)	N_{exp}	N_{jitter}	Int. time (min)
J	1.1	60	10	5	50
H	1.0	60	9	5	45
Ks	0.9	30	6	5	15

1 Myr old burst ($<2'$ from the core) and a somewhat older one (3 Myr). The fields observed in this study cover mainly the oldest regions.

2.1. Preliminary studies at the TBL

As a preliminary step, we used a 2-m class telescope to study the low-mass contents of the Serpens cloud in the near-infrared range. In July 1996 and July 1997, we observed a small field ($5' \times 2'$) in the south-western region of the Serpens cloud, located at about $8'$ from the core, using the Bernard Lyot 2-m telescope (TBL) at the Pic du Midi Observatory. The observations were carried out with MOICAM, a 1–2.5 μm near-infrared 256×256 NICMOS-III camera (<http://bigorre.bagn.obs-mip.fr/tbl/English/main.htm>).

The completeness limits of the survey were 19, 18 and 17 in J , H , and K bands, respectively. This survey has revealed substellar object candidates close to the detection limit of the instrument, indicating that small field observations with a 2-m class telescope was almost able to detect brown dwarfs in a reasonable observing time. Further observations were therefore carried out using SOFI on the NTT. Finally, the TBL instrument was used to monitor the photometry of relatively bright objects and since, we have used MOICAM to obtain complementary observations of BD-Ser 1 (LCMK02) in the J band (see Sect. 4.3).

2.2. NTT/SOFI NIR photometric observations

The photometric observations in the J , H and Ks bands were carried out with the ESO 3.5-m NTT at La Silla on July 25–27, 1999. The SOFI camera, equipped with a 1024×1024 HgCdTe (HAWAII) array, was used in the Large Field mode covering $5' \times 5'$ with a spatial sampling of $0.29''/\text{pixel}$. The average seeing was about $1''$ during the three nights.

Two adjacent fields in the Serpens cloud were observed including the area imaged during TBL observations. Various series of 60 s exposures in J and H , and 30 s in Ks band filters were repeated five times and offset to remove the sky background and cosmic rays (see Table 1 for a journal of the observations). The data processing was performed with the *jitter* image processing package in the ECLIPSE software (Devillard 1999).

Dark frames were obtained during twilight with the same integration time as the target frames. All frames in a given band

Fig. 1. SOFI *JHK* infrared color composite image of the field observed towards the Serpens cluster. North is up and east is left and the field of view is about $10' \times 5'$. The dark region to the northeast is close to SVS76 Ser 2 which is considered as the center of the cluster. The typical seeing of the images used to build this composite is $1''$.

were co-added to provide the final images. Subsequent aperture photometry was performed with the DAOPHOT package in IRAF¹ devoted to crowded fields, assuming a constant PSF across the field of view. Further analysis was conducted with the Interactive Data Language (IDL) and Matlab. Absolute

calibration of the instrumental photometry was performed using zero-point and air-mass corrections derived from standard photometric stars (Persson et al. 1998) that were systematically observed before and after each series of exposures.

Our results were translated from instrumental (*JHK*s) magnitudes to the standard (*JHK*) photometric bands, using relations found in the SOFI user's manual (LSO-MAN-ESO-40100-004). We have also checked the magnitudes of the brightest stars against previous studies (EC92, GCNM98

¹ IRAF is distributed by the National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

Fig. 2. Number of stars versus apparent magnitude of our survey in J , H and K .

and K99). In particular, twenty stars common to the study by EC92 were selected to perform photometry secondary calibration down to a ± 0.05 mag uncertainty.

The Besançon model of stellar population synthesis (Reylé & Robin 2001) (http://www.obs-besancon.fr/www/modele/modele_ang.html) predicts that the maximum number of stars occurs at magnitudes larger than the highest bars of Fig. 2. Therefore, we assume our completeness limits to be the highest bars in the Fig. 2, i.e. 21, 19.5, and 19 in J , H , and K respectively (see Fig. 2).

From these photometric results, we used a preliminary version of the method described in Sect. 3 and 17 brown dwarf candidates were selected to be observed by spectroscopy.

2.3. Astrometry

The Guide Star Catalog II (GSC II²) was used to derive accurate astrometry. Five stars of this catalog were found in our $5' \times 10'$ field of view. A first order polynomial was fitted to the gnomonic projection, and the astrometry we derived is estimated to be accurate within a rms of $0.06''$.

² The Guide Star Catalogue-II is a joint project of the Space Telescope Science Institute and the Osservatorio Astronomico di Torino. Space Telescope Science Institute is operated by the Association of Universities for Research in Astronomy, for the National Aeronautics and Space Administration under contract NAS5-26555. The participation of the Osservatorio Astronomico di Torino is supported by the Italian Council for Research in Astronomy. Additional support is provided by European Southern Observatory, Space Telescope European Coordinating Facility, the International GEMINI project and the European Space Agency Astrophysics Division.

At the end of the process, astrometric and photometric data were obtained for 3085 objects measured in H and K , among which 1958 were detected in J , H and K . The complete data list, with all objects detected in each color can be downloaded from the *Centre de Données Stellaires*, Strasbourg.

2.4. Color-color and color-magnitude diagrams

The infrared color-magnitude diagrams ($J - H$, H) and ($H - K$, K) of the whole observed region are presented in Fig. 3. In these diagrams, we compare the distribution of sources with the location of Baraffe et al. (1998, hereinafter BCAH98) low-mass pre-main sequence star and brown dwarf isochrones (grainless model, $[M/H] = 0$ and $Y = 0.275$), using the distance of 259 pc for the cluster (Straizys et al. 1996) and an age of 3 Myr (GCNM98). For such parameters, our survey is sensitive to a $20 M_{\text{Jup}}$ object seen through an absorption of $A_V \sim 16$.

The ($J - H$, $H - K$) color-color diagram of the whole observed region is presented in Fig. 4. From this diagram, we can derive the average reddening of the region to be $A_V \sim 8$. Most of the sources fall in an area bounded by the reddening vectors for the giant branch and the tip of the dwarf sequence. 139 sources have infrared colors right of the reddening vector from M6 dwarfs (see Fig. 4). These sources have infrared excess and are considered to be members of the Serpens cloud having optically thick circumstellar disks. The detailed method used to determine the sources parameters is described in the following section.

3. Extinction and cluster membership

Luminosity functions and star membership of young stellar clusters are generally derived from differential star counting, hence requiring the luminosity function of field stars. This function can be evaluated by two independent methods: i) another image of a nearby star field is obtained using similar observing conditions (see e.g., Brandl et al. 1999); ii) a theoretical distribution of field stars is computed from a galactic model (see e.g., Eisenhauer et al. 1998).

The dark cloud associated with the Serpens cluster extends up to tens of arcmins with possible $A_V > 5$, and no nearby star field without strong extinction variations can be found at a distance less than 1° . As the cluster is close to the galactic plane, such a distance is not adapted to measure a relevant reference star field. A modeled field star distribution could be evaluated, using e.g. the Besançon model of stellar population synthesis (Reylé & Robin 2001). This model uses Monte-Carlo simulation and provides a complete census of the stars properties (distance, apparent magnitude, spectral type and interstellar A_V) for any line of sight from the distribution of star densities in the Galaxy. In order to smooth the results of the model, ten tries were computed and averaged. However, due to the situation of the Serpens cloud in the galaxy, the model provides large numbers of stars with corresponding large statistical uncertainties that overwhelm the number of cloud stars in magnitude bins.

As no statistical counting method can be used, we developed a method called “photometric parallax” to derive as a

Fig. 3. Infrared color–magnitude diagrams for all 1958 sources detected in *JHK* in our survey. The locations of the sources are compared to the location of 3 Myr pre-main sequence isochrones (BCAH98) at the distance of the Serpens cluster. Reddening vectors from Rieke & Lebofsky (1985) with length $A_V = 8$ are drawn for 0.5, 0.2 and 0.02 $M_\odot$ objects at the cluster age. The dot-dashed line indicates our completeness limits.

whole the extinction, the distance and the spectral type on a star by star basis, from its *J*, *H*, and *K* magnitudes.

3.1. Star sorting method

The “photometric parallax” method is comparable to the Near Infrared Color Excess (NICE) approach described by Lada et al. (1994, hereinafter LLCB94). For the two methods, the observed field is divided regularly in square cells.

The extinction is computed for each cell with the photometric properties of the stars. The cell dimension is a compromise between small values to have the best resolution possible and larger values to have enough stars to evaluate the extinction (typically half a dozen per cell). Alves et al. (1998) (hereinafter ALL98) used NICE with cells of (0.2 pc) at the distance of their target. In our study the cells are much smaller, ~ 0.02 pc at the distance of the Serpens cloud.

The NICE method assumes a simple relation between the extinction and the $(H-K)$ color, the latter being computed from a nearby control field. ALL98 found the following relation:

$$A_V = 15.87 \times E(H-K). \quad (1)$$

In this relation, all objects are assumed to be late dwarfs with a mean intrinsic $(H-K)$ color of about 0.2 mag.

We extend the application domain of the method by taking also into account giants and 3 Myr PMS stars (adopted age of the Serpens cluster), and we distinguish early/late (respectively hot/cold) objects as in the following list:

- early dwarfs (B9V to K5V);
- late dwarfs (K6V to M6V);
- early giants (B9III to M0III);
- late giants (M1III to M6III);
- early young PMS objects ($1.2 M_\odot$ to $0.9 M_\odot$);

- late young PMS objects and brown dwarfs ($0.9 M_\odot$ to $0.02 M_\odot$).

In Fig. 5, the upper panel is the $(H-K, J-H)$ color–color diagram and the lower panel is the $(H-K, K)$ color–magnitude diagram. In both panels, we have plotted 3 sequences:

- the observed Zero Age Main Sequence (hereafter ZAMS) for the dwarfs;
- the location of the giants (Landolt & Börnstein 1982; Bessell & Brett 1988; Kenyon & Hartmann 1995);
- the 3 Myr old pre-main sequence isochrone from BCAH98.

Starting from the star symbol representing a random object (O), we deredden it toward the various star sequences using the Rieke & Lebofsky law (1985): $A_J = 0.282 \times A_V$, $A_H = 0.175 \times A_V$, and $A_K = 0.112 \times A_V$. Depending on the star position in the color–color diagram, two A_V solutions can be found for each sequence (early and late): OB1 and OA1. Each extinction value is reported in the bottom color–magnitude diagram as OB2 and OA2 segments. Then, the corresponding distance modulus of the object can be derived from the vertical segments B2B3 and A2A3 in the bottom panel of Fig. 5.

Different possible (A_V, DM) pairs are therefore assigned to a given object. Up to 3 solutions for ZAMS stars, and up to 2 for giants and for 3 Myr low-mass stars and brown dwarfs are possible, yielding up to six possible solutions per object. In the following, we describe how we extract the objects’ parameters, taking in to account only the case of stars without infrared excess (see Fig. 4).

Along a given line of sight, the extinction is the superposition of the galactic extinction (mostly farther from the cloud) and the local step of extinction due to the Serpens cloud. We used the galactic extinction law defined by Bahcall & Soneira (1980, hereafter BS80) that reads:

$$A_V = a_{\text{inf}} \times (1 - \exp(-z/100)) \quad (2)$$

Fig. 4. Infrared color-color diagram for all 1958 sources detected in *JHK* in our survey. The observed color-color distribution is compared with field dwarf and giant sequences (grey solid lines, Landolt & Börnstein 1982; Bessel & Brett 1988; Kenyon & Hartmann 1995). The dark solid line is the 3 Myr sequence for low mass stars and brown dwarfs, the dotted line show the locus of T Tauri stars (Meyer et al. 1997) and the dash-dotted lines show the absorption vectors.

where $a_{\text{inf}} = 0.15/\sin b$, $z = \sin b \times 10^{((DM+5)/5)}$, b being the galactic latitude and DM the distance modulus of the star. The galactic visual extinction increases slowly as a sigmoid function along the line of sight of the Serpens cloud ($l = 31.53^\circ$, $b = 5.39^\circ$) to reach an asymptotic value of 1.6. This value is much lower than the possible extinction step due to the Serpens cloud itself (average $A_V = 8$, see Fig. 4).

3.2. Stars detected in *J*, *H* and *K*

As a first step, all objects in a cell are assumed to be late dwarfs farther than the Serpens cloud as in the NICE method. This starting hypothesis is reasonable since late (G-K-M) dwarfs are the most abundant stars in the Galaxy and since the Serpens cloud is close. Then, the median extinction in a cell is computed and compared to the extinction of each individual object detected in all three (*J*, *H* and *K*) bands. Finally we use the following algorithm, trying to minimize the A_V root mean square (rms) in a cell:

1. Objects (firstly assigned as late dwarfs) used to compute the median A_V value and its rms are corrected for the galactic extinction (BS80).
2. Objects with $DM < DM_{\text{Serpens}}$ are considered as early giants with $DM \leq 15$ if their A_V is consistent with the mean value of the cell. Indeed, at $DM = 15$, ($d = 10^4$ pc), the corresponding height above the galactic plane in the direction of the Serpens cloud is $z = 940$ pc. According to BS80, the giants' height scale is 250 pc. The ratio $\rho(z = 940 \text{ pc})/\rho(\text{galacticplane})$ for giants stellar

Fig. 5. ($J - H$, $H - K$) color-color (top panel), and (K , $H - K$) color-magnitude (bottom panel) diagrams explaining the assignment of the visual extinction (A_V) and the distance modulus (DM) for a given object represented as a star symbol (see text). The solid line represents the observed dwarfs ZAMS, the dashed line the giants, and the dot-dashed line the 3 Myr low-mass stars and brown dwarfs (BCAH98).

density is only 0.02 and giants should be marginally found when $DM > 15$.

3. Objects with A_V 2 mag higher than the cell median A_V are assigned to cooler stars. Late giant assignation is chosen if $DM \leq 15$.
4. Objects with A_V 2 mag lower than the median A_V are assigned to hotter stars. Early giant assignation is chosen if $DM \leq 15$ otherwise they are considered as early dwarfs.
5. Objects are considered as young Serpens members if their distance modulus ranges from 6 to 8.

At this point, (A_V , DM) and (A_V , $\text{rms}(A_V)$) pairs are assigned to 1808 objects (the 139 infrared excess objects are not used) detected in all three *J*, *H*, and *K* bands, in about half of the cells. This first step allows us to generate an extinction map up to $A_V = 15$ (see second image in Fig. 6).

In their previous studies, LLCB94 and ALL98 found a correlation between the A_V value and its rms over a cell (of 0.2 pc). They proposed that unresolved substructures can explain such a tendency. In our study, the cells are 100 times smaller (≈ 0.02 pc) so we have access to even finer substructures of the cloud. Our A_V rms values are twice smaller, for a given A_V value, than previous studies and, as expected, the correlation we find between the A_V value and its rms is less pronounced.

Fig. 6. Evolution of the extinction map built through the three different steps explained in the text. The image on the left panel is the $10' \times 5'$ mosaic observed in the K_s band filter with the SOFI camera on the NTT. North is up and east is left. The three extinction maps are derived from the three different steps (JHK stars, HK stars and stellar densities, respectively). The map on the right panel is the final extinction map, and the A_V scale is given.

3.3. The case of incompletely detected stars

For objects detected in H and K bands only, the method described above cannot be used. We assume again that all remaining objects are late dwarfs. Then, the method can still be applied even if the J magnitude is larger than the completeness limit. This second step allows us to assign (A_V, DM) and $(A_V, \text{rms}(A_V))$ pairs to a total of 2945 objects, as well as the extinction for 71% of the cells (see third image in Fig. 6).

Finally, for cells with objects only detected in K , we applied the stellar density method to assign (A_V, DM) pairs. From our previous photometric method in the other cells, we could fit a relation between the number of stars in a cell and the visual extinction:

$$A_V \sim 30 - 3 \times N_C \quad (3)$$

where N_C is the number of stars in the cell. We then used this formula to assign an A_V value to the remaining 29% of cells having only K detections (see fourth image in Fig. 6). We stress, however, that this computation is valid only for $15'' \times 15''$ cells and remains uncertain.

The final extinction map is shown on the right panel of Fig. 6. It reveals a highly extinguished region in the north-east part of the mosaic, already seen on the composite image (Fig. 1). Indeed, this region is located close to the SVS2 source, considered as the core of the cloud. Furthermore, a filament is detected in the centre of the field. Its northern part is highly extinguished ($A_V \geq 20$) while its southern part is splitted into two fainter arms with $A_V \sim 13$. Besides these features, the general trend shows extinction higher than 5, a value consistent with the small number of detections on the POSS photographic plates. Note that the extinction map is computed from background stars only. If other clouds are located between the Serpens cloud and the farthest stars, their extinction has been added to the map, and we can not disentangle it from the Serpens one.

4. Discussion

The accuracy of the spectral type assignment arises from the quality of the photometry and the intrinsic color dispersion of the stars. As seen in Fig. 5 of the Bessell & Brett (1988) paper, the thickness of the dwarf main sequence in the color-magnitude diagram is ± 0.5 mag. Therefore, we assigned an uncertainty of ± 1 mag to the A_V and DM values for all objects (assuming a distance uncertainty for the Serpens cloud of ± 0.5 in DM). The thickness of the main sequence in the $(H - K, J - H)$ color-color diagram (Bessell & Brett 1988) is about 0.1 mag, corresponding to an uncertainty of about ± 300 K on the effective temperature of the stars, hence the corresponding uncertainty for spectral type assignment. The influence of double stars should also be addressed as it is known that in the solar neighborhood, 50% of the field stars are binaries or multiple systems (Duquennoy & Mayor 1991; Fisher & Marcy 1992). If an object is an unresolved double star, the distance we derive is underestimated at worst by a factor of 1.4 if both components have the same spectral type. On the other hand, the corresponding visual extinction is wrong by up to 2 mag in the case of a combination of very different spectral types.

4.1. Members of the Serpens cluster

As a consequence of the uncertainty on the distance modulus, a star in the Serpens cloud can be found anywhere in the distance range of 160 to 410 pc in our data. We extracted stars in this range and assumed they can be members of the Serpens cloud, keeping in mind that some of them could be background stars. We found a total of 62 stars, among which 14 fall on the 3 Myr sequence of mass smaller than $0.8 M_\odot$.

The remaining 48 objects are compatible with zero age main sequence (ZAMS) late dwarfs. This number is more than twice the number of stars predicted along this line of sight by the Besançon model of stellar population synthesis

Table 2. Low mass stars ($<0.8 M_{\odot}$) of the Serpens cloud measured in this study are presented as their apparent magnitudes, coordinates, A_V and estimated masses from BCAH98 isochrones for 3 Myr. Three brown dwarf candidates lie in the top of the table ($<0.075 M_{\odot}$). Note that the astrometric position of BD-Ser 1 is slightly different from that published by LCMK02. It was refined with the GSC II catalog and is considered to be better.

Name	RA (J2000)	Dec (J2000)	J	H	K	A_V	Lum ($L_{\odot}$)	Mass ($M_{\odot}$)
BD-Ser 1	18 29 53.12	+01 12 27.6	17.32 ± 0.05	15.57 ± 0.05	14.54 ± 0.05	10.7	6.2×10^{-3}	0.030 ± 0.02
BD-Ser 2	18 29 46.20	+01 08 56.0	16.23 ± 0.05	15.33 ± 0.05	14.76 ± 0.05	2.9	1.0×10^{-2}	0.038 ± 0.02
BD-Ser 3	18 29 47.17	+01 16 01.5	19.96 ± 0.15	17.46 ± 0.10	15.96 ± 0.05	17.8	1.3×10^{-2}	0.045 ± 0.02
	18 29 45.68	+01 11 12.2	16.23 ± 0.05	14.37 ± 0.05	13.36 ± 0.05	10.9	7.6×10^{-2}	0.19 ± 0.02
	18 29 43.77	+01 10 47.1	13.56 ± 0.05	11.75 ± 0.05	10.97 ± 0.05	9.6	4.4×10^{-1}	0.70 ± 0.05
	18 29 42.36	+01 12 01.9	16.75 ± 0.05	14.13 ± 0.05	12.78 ± 0.05	17.6	1.6×10^{-1}	0.33 ± 0.02
	18 29 48.79	+01 13 42.0	17.64 ± 0.05	14.99 ± 0.05	13.55 ± 0.05	18.2	1.0×10^{-1}	0.24 ± 0.02
	18 29 44.73	+01 13 50.9	17.04 ± 0.05	13.95 ± 0.05	12.41 ± 0.05	21.6	4.4×10^{-1}	0.70 ± 0.05
	18 29 43.12	+01 15 01.1	16.95 ± 0.05	15.16 ± 0.05	14.17 ± 0.05	10.3	5.9×10^{-2}	0.16 ± 0.02
	18 29 42.53	+01 16 19.1	21.06 ± 0.20	17.14 ± 0.10	14.97 ± 0.05	30.0	1.1×10^{-1}	0.26 ± 0.04
	18 29 41.92	+01 17 13.4	18.62 ± 0.10	15.38 ± 0.05	13.71 ± 0.05	23.1	2.8×10^{-1}	0.50 ± 0.03
	18 29 39.78	+01 17 11.8	15.28 ± 0.05	12.92 ± 0.05	11.79 ± 0.05	14.8	4.0×10^{-1}	0.63 ± 0.04
	18 29 37.49	+01 14 54.1	14.46 ± 0.05	13.05 ± 0.05	12.41 ± 0.05	6.2	1.6×10^{-1}	0.33 ± 0.02
	18 29 34.09	+01 17 29.3	14.83 ± 0.05	12.52 ± 0.05	11.43 ± 0.05	14.3	4.3×10^{-1}	0.68 ± 0.05

(Reylé & Robin 2001), which gives 19 ± 4 stars (evaluated from 10 tries). However, some of those excess stars can be discarded as unresolved binaries. Given the separation distribution of Duquennoy & Mayor (1991) for a $1 M_{\odot}$ star, at an average distance of 300 pc, about 3/4 of the double stars will be unresolved with a seeing of $1''$ (see Table 1). This yields up to 18 unresolved binaries in our sample, thus we remain with 30 ± 7 stars against 19 ± 4 expected; these estimations are consistent at the 1σ level.

We did not make any attempt to extract stars of mass higher than $1.2 M_{\odot}$ (mass limit of the BCAH98 model). For stars between 0.8 and $1.2 M_{\odot}$, the location of the upper elbow of the stars 3 Myr old in the color–color diagram does not allow accurate assignments (see Fig. 5). As a consequence, young stars with masses higher than $0.8 M_{\odot}$ were assigned to be ZAMS stars, yielding supplementary objects compared to the Besançon model.

We then end with a lower limit of 14 objects of masses less than $0.8 M_{\odot}$ detected by *JHK* photometry in the $5' \times 10'$ field. This number is limited by our sensitivity in *J* and by the fact that we do not take into account stars with infrared excess.

Such a small number forbids construction of a realistic luminosity function nor a mass function for the Serpens cluster. However, it is remarkable that among these 14 objects, 3 fall in the $0-0.15 M_{\odot}$ mass bin and have masses estimated lower than $0.045 M_{\odot}$ (see Table 2).

We stress that our method applies only to stars without infrared excess. We thus left aside 139 objects whose age, mass and distance cannot be determined using *JHK* photometry only. Some of these objects could be T Tauri stars with disks, and even brown dwarfs with disks. In the following section, we study the 14 “naked” low mass stars.

Fig. 7. Mass histogram of the 14 young stars of the Serpens cluster with a mass smaller than $0.8 M_{\odot}$. The three stars in the $0-0.15 M_{\odot}$ bin are brown dwarfs candidates with $M < 0.045 M_{\odot}$.

4.2. Low mass star contents

Figure 7 shows the mass distribution for the 14 “naked” young stars found to be members of the Serpens cloud.

No clear fluctuation is seen between 0.1 and $0.8 M_{\odot}$, but the small number of stars involved gives this result little statistical confidence. The left bin includes all stars with $M \leq 0.15 M_{\odot}$, amongst them the dwarfs candidates. The characteristics of these objects are reported in Table 2. The three stars lie in the mass range compatible with the brown dwarfs ($M \leq 0.045 M_{\odot}$). BD-Ser 1, which 1.2 to $2.4 \mu\text{m}$ spectrum has been already published in LCMK02 is one of them. Its spectrum is of type L2 and, from Chabrier et al. 2000 models, it will become a T type star at 100 Myr (LCMK02).

Theoretical studies of dynamical evolution of stars in clusters show that a part of the initial low mass stars could be ejected from the cluster (Reipurth & Clarke 2001). Regarding the spatial distribution of stars in the Serpens clouds (from this study and those of EC92 and K99), we assume that the half

Table 3. J , H and K magnitudes of BD-Ser 1 at different dates and using various instruments. Uncertainties are 1σ . n-d means no data. The * symbol means that date is for the J image.

Date	J	H	K	References
1988 Jul. or 1989 May	15.9	15.4	14.4	EC92
1995 Aug. or 1996 Aug.	17.23 ± 0.17	15.54 ± 0.06	14.46 ± 0.05	K99
1996 Jul. or 1997 Jul.	18.2 ± 0.4	15.4 ± 0.1	14.4 ± 0.1	GCNM98
1999 Jul. 26 23:04	17.38 ± 0.04	n-d	n-d	This study NTT-SOFI
1999 Jul. 26 23:44*	17.26 ± 0.02	15.57 ± 0.05	14.54 ± 0.05	This study NTT-SOFI
2002 Mar. 30 04:38	17.19 ± 0.10			This study TBL-Moicam
2002 Sep. 25 20:48	17.31 ± 0.05			This study TBL-Moicam
2003 Apr. 18 04:23	17.04 ± 0.15			This study TBL-Moicam

Fig. 8. J , H and K magnitudes variability of BD-Ser 1. The x axis only display different measures, not time. Error bars are 3σ uncertainties.

mass radius R_{hm} of the cluster is larger than 0.4 pc. According to Adams et al. (2002), the typical velocity dispersion in open clusters is about $v = 2 \text{ km s}^{-1}$. Therefore the derived crossing time (t_c) of the Serpens cluster should be higher than 0.2 Myr. Using an age of 3 Myr for Serpens, we obtain a ratio $\text{age}/t_c < 15$. Figure 8 of Adams et al. (2002) then implies that evaporation of low mass stars should be less than 20%, and we neglect it. If we assume an homogeneous distribution, the three brown dwarfs detected in 1.4 pc^3 yield a few dozen substellar object for the whole cluster. We can expect that some brown dwarfs have escaped our investigation in the most extincted regions with a non homogeneous density distribution. Thus future deep NIR wide field imaging in this cloud should detect a consequent number of young brown dwarfs.

4.3. Brown dwarf variability

If brown dwarfs experience a TTS phase (see e.g., Jayawardhana et al. 2003), variability might be one of their characteristic phenomenon. Monitoring L and T brown dwarfs, Enoch et al. (2003) found that a significant number of them show photometric variability in K s. Concerning the recently spectroscopically confirmed brown dwarf BD-Ser 1 (LCMK02), we have examined data from the literature and ours, spanning 15 years from 1988 to 2003, to check the presence of variability. The results are listed in Table 3 and plotted in Fig. 8.

Fig. 9. Correlation of BDSer1 H and K variations. Four different measures are shown, 2 of them being identical. Error bars are 1σ uncertainties.

Apart from one measurement that appears quite doubtful, there is no evidence that BD-Ser 1 would be variable at the 3σ level in any of the three JHK bands, but there is a trend at the 1σ level. On the other hand, LCMK02 found evidence of accretion in the IR spectrum of the object (Bry emission). If there is accretion ongoing onto BD-Ser 1, it could be associated with signs of variability. We conclude that with the available photometric accuracy, BD-Ser 1 is not variable, but this should to be checked on a longer term and a smaller interval with a photometric accuracy better than 0.05 mag. We have also checked for a relation between H and K variations for which we find the trend of a correlation (see Fig. 9). This could be consistent with IR excess emission variability due to bursts of accretion, even if Preibisch 2003 detected no X-ray emission from BD-Ser 1 using the XMM-Newton observatory. Indeed, he attributed this non detection to a too low sensitivity of the instrument for that target.

5. Conclusion

We have presented a deep near-infrared survey of a 50 square arcmin region in the Serpens cloud with the SOFI camera at the NTT. Such survey, complete down to $K = 19$, allows us to probe the substellar domain despite the high internal extinction of the region. We have designed a complete and powerful method to generate an extinction map and disentangle members from contaminating background objects based on color–magnitude and color–color diagrams. Assuming an age of 3 Myr for the Serpens cloud, luminosity and mass range have been derived for each individual object, revealing 3 substellar candidates in this small field. The Serpens cloud distance being about 260 pc, if our survey is actually complete down to $0.02 M_{\odot}$, we detect about 2 brown dwarfs per cubic parsec, a density close to the average stellar density. One can predict about a hundred young brown dwarfs that should be detected in the whole cluster with a wide NIR field imager.

This method, associated with very accurate photometric observations of dense star clusters gives a very powerful tool to select brown dwarf candidate members that can be spectroscopically confirmed later. A photometric follow-up performed at the TBL on BD-Ser 1 did not reveal significant 3σ variability. However, a possible correlation between H and K magnitudes variation in this object could indicate NIR excess emission due to bursts of accretion, a result consistent with the possible detection of a Br γ line emission in the spectrum of BD-Ser 1.

Acknowledgements. We thank the ESO support staff for their help during the observations. This research has made use of NASA's Astrophysics Data System Bibliographic Services. N.L. and J.L.M. thank the E.C. Research Training Network "The Formation and Evolution of Young Stellar Clusters" for financial support (HPRN-CT-2000-00155). We thanks also Annie Robin and Isabelle Baraffe who kindly provided us with complementary data from their theories.

References

- Adams, T., Davies, M. B., Jameson, R. F., & Scally, A. 2002, *MNRAS*, 333, 547
- Alves, J., Lada, C., Lada, E., et al. 1998, *ApJ*, 506, 292
- Bahcall, J. N., & Soneira, R. M. 1980, *ApJS*, 44, 73
- Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, *A&A*, 337, 403
- Barrado y Navascués, D., Stauffer, J. R., Bouvier, J., et al. 2001a, *ApJ*, 546, 1006
- Barrado y Navascués, D., Stauffer, J. R., Briceno, C., et al. 2001b, *ApJS*, 134, 103
- Barrado y Navascués, D., Bouvier, J., Stauffer, J. R., et al. 2002, *A&A*, 395, 813
- Béjar, V. J. S., Martín, E. L., Zapatero Osorio, M. R., et al. 2001, *ApJ*, 556, 830
- Bessel, M. S., & Brett, J. M. 1988, *PASP*, 100, 1134
- Bontemps, S., André, P., Kaas, A. A., et al. 2001, *A&A*, 372, 173
- Bouvier, J., Stauffer, J. R., Martín, E. L., et al. 1998, *A&A*, 336, 490
- Brandl, B., Brandner, W., Eisenhauer, F., et al. 1999, *A&A*, 352, L69
- Burgasser, A. J., Liebert, J., Kirkpatrick, J. D., et al. 2002, *AJ*, 123, 2744
- Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. 2000, *ApJ*, 542, 119
- Casali, M. M., Eiroa, C., & Duncan, W. D. 1993, *A&A*, 275, 195
- Comerón, F., Neuhäuser, R., & Kaas, A. A. 2000, *A&A*, 359, 269
- Davis, C. J., Matthews, H. E., Ray, T. P., et al. 1999, *MNRAS*, 309, 141
- D'Antona, F., & Mazzitelli, I. 1997, *Mem. Soc. Astron. It.*, 68, 807
- Devillard, N. 1999, *ADASS VIII, ASP Conf. Ser.*, 172, 333
- Delfosse, X., Tinney, C. G., Forveille, T., et al. 1997, *A&A*, 327, L25
- Delfosse, X., Tinney, C. G., Forveille, T., et al. 1999, *A&AS*, 135, 41
- Duquennoy, A., & Mayor, M. 1991, *A&A*, 248, 485
- Eiroa, C., & Casali, M. M. 1992, *A&A*, 262, 468
- Eisenhauer, F., Quirrenbach, A., Zinnecker, H., & Genzel, R. 1998, *ApJ*, 498, 278
- Enoch, M. L., Brown, M. E., & Burgasser, A. J. 2003, *AJ*, 126, 1006
- Fisher, D., & Marcy, G. 1992, *ApJ*, 396, 178
- Giovannetti, P., Caux, E., Nadeau, D., & Monin, J.-L. 1998, *A&A*, 330, 990
- Hawley, S. L., Covey, K. R., Knapp, G. R., et al. 2002, *AJ*, 123, 3409
- Hillenbrand, L. A., & Carpenter, J. M. 2000, *ApJ*, 540, 236
- Hodgkin, S. T., Pinfield, D. J., Jameson, R. F., et al. 1999, *MNRAS*, 310, 87
- Jayawardhana, R., Mohanty, S., & Basri, G. 2003, *ApJ*, 592, 282
- Jeffries, R. D., Thurston, M. R., & Pye, J. P. 1997, *MNRAS*, 287, 350
- Kaas, A. A. 1999, *AJ*, 118, 558
- Kenyon, S., & Hartmann, L. 1995, *ApJS*, 101, 117
- Kirkpatrick, J. D., Reid, I. N., Liebert, J., et al. 1999, *ApJ*, 519, 802
- Kirkpatrick, J. D., Dahn, C. C., Monet, D. G., et al. 2001, *AJ*, 121, 3235
- Lada, C. J., Lada, E. A., Clemens, D. P., & Bally, J. 1994, *ApJ*, 429, 694
- Landolt, H., & Börnstein, R. 1982, *Astronomy & Astrophysics*, ed. K. Schaifers, & H. H. Voigt (Springer-Verlag)
- Lodieu, N., Caux, E., Monin, J.-L., et al. 2002, *A&A*, 383, L15
- Lucas, P. W., & Roche, F. P. 2000, *MNRAS*, 314, 858
- Lucas, P. W., Roche, F. P., Allard, F., & Hauschildt, P. H. 2000, *MNRAS*, 326, 695
- Martín, E. L., Dougados, C., Magnier, E., et al. 2001b, *ApJ*, 561, L195
- Meyer, M. R., Calvet, N., & Hillenbrand, L. A. 1997, *AJ*, 114, 288
- Moorwood, A. F. M., & Spyromilio, J. 1997, in *The Early Universe with the VLT*, ed. Jacqueline Bergeron (Springer), 21
- Moraux, E., Bouvier, J., Stauffer, J. R., & Cuillandre, J.-C. 2003, *A&A*, 400, 891
- Muench, A. A., Lada, E. A., Lada, C. J., et al. 2001, *A&AS*, 199, 7901
- Muench, A. A., Lada, E. A., Lada, C. J., et al. 2003, *AJ*, 125, 2029
- Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., et al. 1995, *Nature*, 378, 463
- Persson, S. E., Murphy, D. C., Krzeminski, W., et al. 1998, *AJ*, 116, 2475
- Pickles, A. J. 1998, *PASP*, 110, 863
- Preibisch, T., & Zinnecker, H. 2001, *AJ*, 121, 1040
- Preibisch, T. 2003, *A&A*, 410, 951
- Rebolo, R., Zapatero Osorio, M. R., & Martín, E. L. 1995, *Nature*, 377, 129
- Reylé, C., & Robin, A. C. 2001, *A&A*, 373, 886
- Rieke, G. H., & Lebofsky, M. J. 1985, *ApJ*, 288, 618
- Reipurth, B., & Clarke, C. 2001, *AJ*, 122, 432
- Sogawa, H., Tamura, M., Gatley, I., et al. 1997, *AJ*, 113, 1057
- Straizys, V., Ernis, K., & Bartait, S. 1996, *Baltic Astron.*, 5, 125
- Strom, S. E., Vrba, F. J., & Strom, K. M. 1976, *AJ*, 81, 638