**A&A manuscript no.**
(will be inserted by hand later)

**Your thesaurus codes are:**
**13.09.6; 08.06.2; 08.16.5; 08.12.3;**

ASTRONOMY
AND
ASTROPHYSICS
25.10.1996

# ISOCAM observations of low-luminosity young stellar objects in the Chamaeleon dark clouds*

**L. Nordh[1] & G. Olofsson[1], A. Abergel[2], Ph. André[3], J. Blommaert[4], S. Bontemps[1], F. Boulanger[2], M. Burgdorf[4], C.J. Césarsky[3], D. Césarsky[2], E. Copet[5], J. Davies[6], E. Falgarone[7], M. Huldtgren[1], A.A. Kaas[1], G. Lagache[2], T. Montmerle[3], M. Perault[7], P. Persi[8], T. Prusti[4], J.L. Puget[2], F. Sibille[9]**

[1] Stockholm Observatory, S-133 36 Saltsjöbaden, Sweden, e-mail: nordh@astro.su.se, olofsson@astro.su.se
[2] Institut d'Astrophysique Spatiale, Université Paris XI, Bât. 121, 91405 Orsay Cedex, France
[3] DAPNIA/SAp, C.E.A. Saclay, 91191 Gif Sur Yvette Cedex, France
[4] ISO, Villafranca del Castillo, ESA Satellite tracking station, P.O. Box 50727, 28080 Madrid, Spain
[5] DESPA, Observatoire de Paris-Meudon, 5 Place Jules Janssen, 92195 Meudon Cedex, France
[6] Joint Astronomy Centre, 660 N. A′Ohoku Place, University Park, Hilo, HI 96720, USA
[7] ENS Radioastronomie, 24 rue Lhomond, 75231 Paris Cedex 05, France
[8] Instituto Astrofisica Spaziale, CNR, v. E. Fermi 21, 00044 Frascati, Italy
[9] Observatoire de Lyon, 69230 Saint Genis Laval, France

Received date; Accepted date

**Abstract.** We report the first results from an ISOCAM survey for low-luminosity, young stellar objects (YSOs) in nearby star formation regions. The present *Letter* concerns three regions within the Chamaeleon dark clouds, with a total area coverage of $\sim$ 0.8 square degrees, representing 35 % of the presently approved survey programme. The survey is conducted in two broad-band filters, LW2 (6.75 $\mu$m) and LW3 (15 $\mu$m), with a somewhat variable sensitivity limit in order to avoid saturation. For the nominal setup with 2.1 seconds integration time and 6 arcsec per pixel the detection limit is 1.9 mJy and 2.5 mJy in LW2 and LW3, respectively.

The Chamaeleon observations demonstrate that embedded YSOs can be effectively separated from background stars through distinctly different [15/6.75] colour indices. This allows us to identify 65 YSO candidates, of which more than 40 % were not previously known. The observed LW3 luminosity function of the identified YSOs seems to be truncated by the sensitivity limit of the survey.

**Key words:** Infrared: stars - Stars: formation - Stars: pre-main sequence - Stars: luminosity function, mass function

* ISO is an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA.

## 1. Introduction

In order to understand the star formation process, an improved knowledge of the luminosity and mass functions of young stellar objects (YSOs) is of vital importance. This information is presently very limited and essentially lacking for $L < 0.1$ L$_\odot$ and $M < 0.1$ M$_\odot$. ISOCAM (Césarsky et al. 1996, Kessler et al. 1996), with its high sensitivity, relatively high spatial resolution and wide spectral coverage, is the ideal tool for providing us with new and better information about the low-luminosity YSOs still embedded in their parental cloud. As a part of the ISO Central Programme we are surveying nearby star formation regions using the two broad filters LW2 (5–8.5 $\mu$m) and LW3 (12–18 $\mu$m) with a sensitivity limit of a few mJy at 15 $\mu$m (about 50 times better than IRAS). This sensitivity makes it possible to detect objects with T-Tauri type spectral energy distributions (SEDs) down to luminosities lower than approximately 0.01 L$_\odot$ for distances smaller than 150 pc (cf. Kenyon & Hartmann 1995). Assuming a normal reddening law (Whittet 1988), 50 magnitudes of visual cloud extinction would only make a difference of a factor 2 in limiting luminosity. With regard to luminosity the above sensitivity suffices to detect contracting objects as small as 0.01 M$_\odot$ if younger than $\sim 2\ 10^5$ years (Nelson et al. 1992).

In this *Letter* we present preliminary results from observations of two active star formation regions in Chamaeleon, Cha I and Cha II and from an inactive adjacent cloud, Cha III. Many investigations have been devoted to the study of the stellar population of these clouds

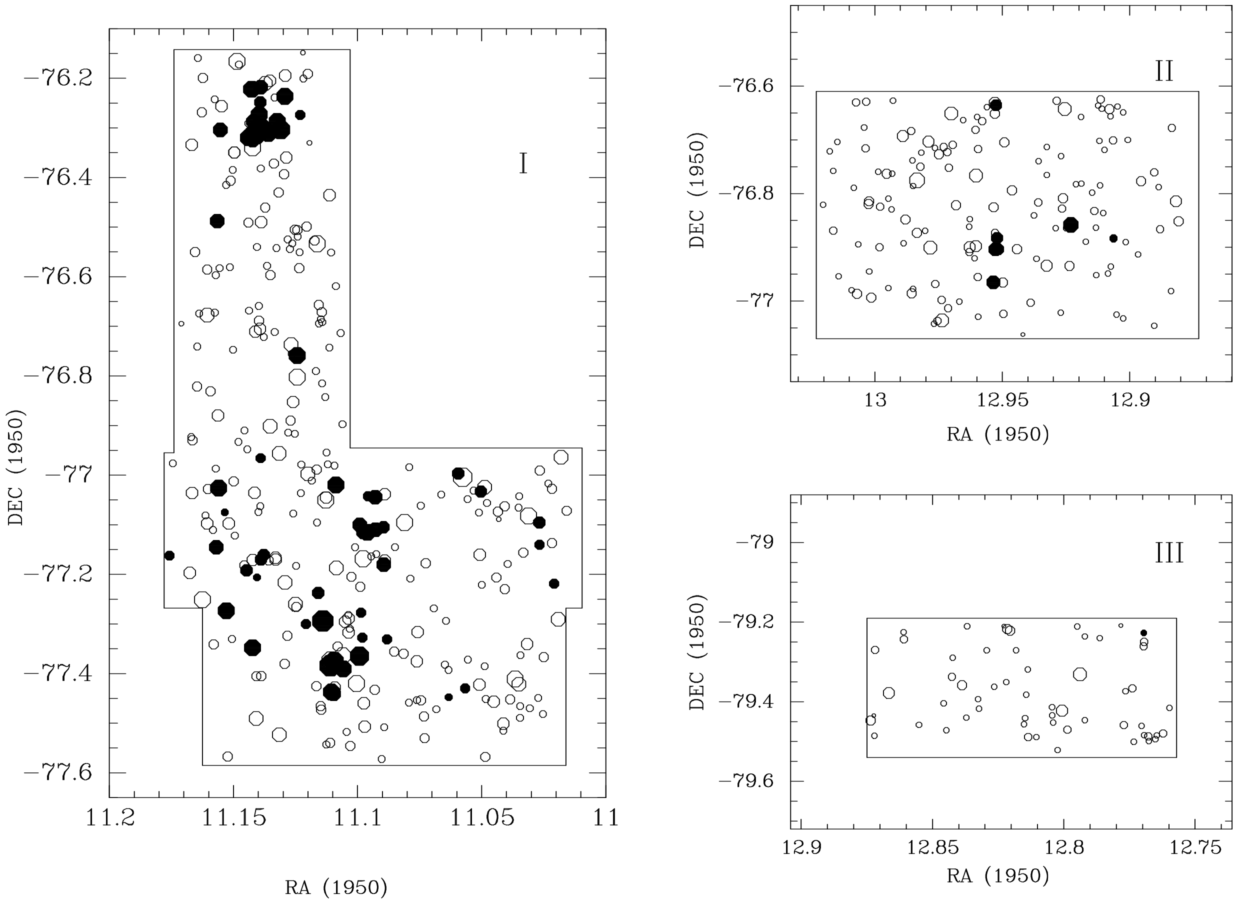


**Fig. 1.** Sky maps of Cha I, Cha II and Cha III showing the spatial distribution of sources detected in LW2 (open) and sources with [15/6.75] > −0.3 (filled). The symbol size is a rough indication of brightness. The borders of the surveyed regions are indicated with straight lines

(see Gauvin & Strom 1992 and references therein). Prusti et al. (1992) have used IRAS data and supplementary ground-based IR photometry to derive a luminosity function for Cha I very similar to that for Taurus. Hartigan (1993) has added 26 new YSOs found in a sensitive H$\alpha$-survey. The Cha I region has also been mapped by ROSAT (Feigelson et al. 1993). A number of X-ray sources (at least 13) have been identified as "weak-lined" T Tauri stars (WTTS) and as many as 80 YSOs were placed in an H-R diagram (Lawson et al. 1996). The inferred range in mass is model dependent but neither of their two model comparisons results in masses less than 0.1 $M_{\odot}$. Even though the median age of these YSOs is about 3 $10^6$ years, the classical signposts of star formation activity (outflows, HH objects) are present (cf. Mattila et al. 1989, Graham & Hartigan 1988). The main purpose of the present ISOCAM observations is to try to detect embedded objects of even lower luminosity and mass.

## 2. Observations and reductions

The survey consists of maps in two broad filters, LW2 (5–8.5 $\mu$m) and LW3 (12–18 $\mu$m). Nominally we use a pixel field of view (PFOV) of 6 arcsec and a unit integration time $t_{\rm int}$ of 2.1 seconds, but in regions with previously known bright sources we use 0.28 s and sometimes PFOV = 3$''$. The observing time spent per position is always $\sim$ 15 seconds. The raw data (> 23000 images) are first darksubtracted. Deglitching is made by median filtering in the time domain of each pixel. Flat-fields are extracted from each raster map by taking the median value of each pixel, excluding frames with nebulosity, and normalizing the resulting image to an average of 1.0 in the central 12 × 12 pixels. Flat-field corrected average images are obtained for each raster position. For regions without nebulosity a sky frame is constructed by taking the median per pixel of the flat-field corrected averages. The Chamaeleon region is particularly simple in this context since it is located at $b^{\rm II} \sim -16\,^{\circ}$ and $\beta \sim -60\,^{\circ}$ and since very few sources are

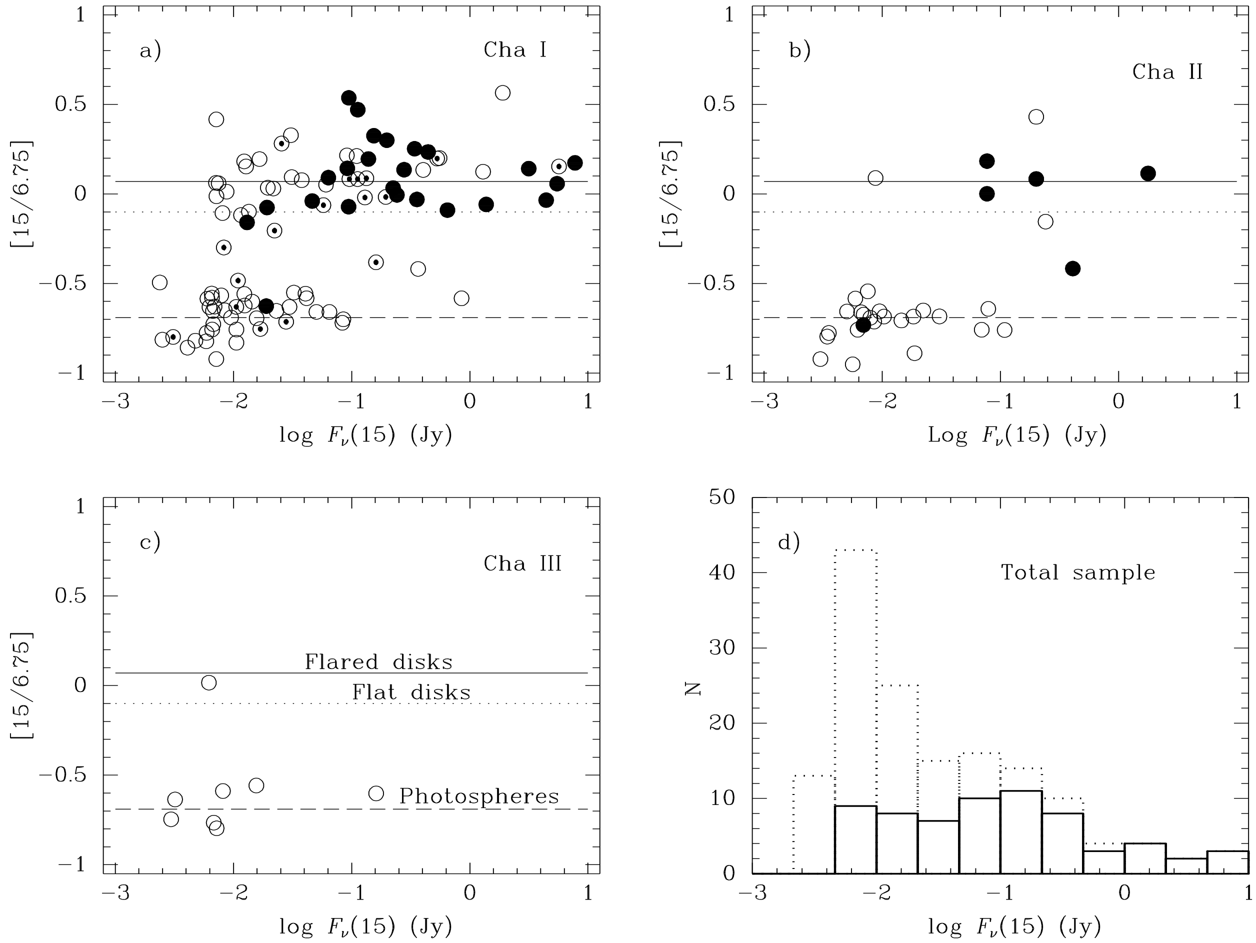


**Fig. 2.** The ISOCAM [15/6.75] colour index, defined as $\log\{F_\nu(15)/F_\nu(6.75)\})$ versus $\log F_\nu(15)$ (Jy), of Cha I, Cha II and Cha III is shown in a), b) and c). Already known YSO candidates are represented with filled circles, large ones for CTTS and embedded objects and small ones for WTTS. Note the clear separation into two distinct colour populations. As an example we have indicated the colours for flat and flared circumstellar disks predicted by models (Kenyon & Hartmann 1995), as well as the colours of normal stellar photospheres. In the histogram for the LW3 filter in d) the red sources are represented by the full line and the total number of LW3 sources by a dashed line

significantly extended. The sky emission is scaled before it is subtracted in order to roughly correct for the long term transient over the raster. The resulting frames are put into a mosaic. Source detection is complicated by the number of "ghost" sources (due to the detector's memory) and glitch remnants and has up to now been performed interactively. An iterative scheme consisting of detection, classification and erasing is followed until only pure noise is left in the mosaic. Classification is based upon the time development of the flux through a small aperture, as well as that of the peak pixel, which enables a clear distinction between glitches, memory effects and sources to be made. Fluxes are obtained by aperture photometry (on each overlap) using small apertures ($r_{ap} = 2$ pixels for PFOV $= 6''$ and $r_{ap} = 3$ pixels for PFOV $= 3''$) and applying aperture corrections thereafter. Due to the short time spent per raster position we have to correct for the effect of a non-stabilized signal. Preliminary calibration data have shown that only about 60 % of the stabilized signal is generally obtained at the beginning of a measurement; this correction has been applied to the data. The transformation from ADU/s to flux units is 1.75 ADU/sec/mJy/pix for LW2 and 1.57 ADU/sec/mJy/pix for LW3 (ISOCAM photometry version 1-c). We stress that no colour correction has been applied yet.

The detection limit is 1.9 mJy for LW2 and 2.5 mJy for LW3 in the regions where $t_{\rm int} = 2.1$ s and PFOV $= 6''$ are used, which comprises Cha II and Cha III as well as 68 % of Cha I. Lowering the integration time to 0.28 s corresponds to a loss in sensitivity by a factor 2; about 15 % of Cha I have been observed with this sensitivity. The use of $t_{\rm int} = 0.28$ s and PFOV $= 3''$, which was necessary in a region comprising 17 % of Cha I, lowers the above sensitivity by a factor of $\sim$ 4. The internal photometric scatter, i.e. the standard deviation between repeated measurements of the same source on different locations of the detector, is better than 10 % for $F_\nu(6.75) \geqq 30$ mJy and $F_\nu(15) \geqq 80$ mJy, better than 20 % for $F_\nu(6.75) \geqq 8$ mJy and $F_\nu(15) \geqq 30$ mJy, and better than 30 % for $F_\nu(6.75) \geqq 4$ mJy and $F_\nu(15) \geqq 10$ mJy. The *absolute* photometric uncertainty is presently 20 %.

## 3. Results and discussion

Altogether we have (so far) detected 524 sources in LW2 and 153 in LW3, and practically all LW3 sources have counterparts in LW2. The spatial distribution is shown in Fig. 1 with symbol size proportional to flux.

As clearly demonstrated in Fig. 2 a) - c) the colour index [15/6.75] separates the objects in two distinctly different groupings, one "red" with $[15/6.75] \sim 0.1$ and one "normal" with $[15/6.75] \sim -0.7$, over a 15 $\mu$m flux interval of almost 4 orders of magnitude. A colour index of $\sim -0.7$ is expected for stars with Rayleigh-Jeans type SEDs. A visual extinction of 20 magnitudes would change this colour index by merely 0.1 dex. Sources with $[15/6.75] > -0.3$ consequently have intrinsic mid-IR excesses and we find it natural to tentatively identify them as YSO candidates.

There are in fact several observations, which independently support our identification of the "red" objects being YSOs. As can be seen in Fig. 2 a) - c), previously known YSOs show a strong tendency to belong to the "red" group. In fact, 28 out of 30 known "classical" T Tauri stars (CTTS) and embedded YSOs and 12 out of 17 known WTTS belong to the group of stars with an LW3 excess. Furthermore, as shown in Fig. 1 the "red" objects in Cha I are distributed in essentially two groups, a denser one around the reflection nebula Ced 112 and a less confined one around Ced 110 and Ced 111. In neither Cha II nor Cha III, however, no similar concentrations are visible, but it has to be remembered that our survey covers only a small part of the Cha II star formation region and that no indication of star formation has yet been found in Cha III (although we find one tentative YSO within our map).

As a third evidence of support it can be noted that circumstellar disks are believed to be common among YSOs, especially CTTS, and potentially responsible for mid-IR excesses similar to those observed in our ISOCAM survey. As shown in Fig. 2 a) - c) the colour index of a "flared" disk model by Kenyon & Hartmann (1995) represents in fact the observed [15/6.75] colour quite well. If the disk hypothesis is correct any model must predict a [15/6.75] colour index essentially constant over a 15 $\mu$m flux interval of almost 4 orders of magnitude, and presumably also over a very wide range of luminosities.

In view of the circumstellar disk hypothesis it may seem surprising that such a high percentage of the WTTS shows this mid-IR excess considering the low detection rate of dust emission from such stars in the mm-continuum surveys (11 % of the WTTS in Taurus-Auriga, see Osterloh & Beckwith, 1995). However, it should be mentioned that a few WTTS in Taurus-Auriga have excess emission at 10 $\mu$m (fig. 3 in André & Montmerle 1994).

Finally, it is interesting to note that the LW3 luminosity function of the putative YSOs, represented by the full line in Fig. 2 d), seems to be truncated by the sensitivity limit of our survey. The significance of this important observational result deserves further analysis.

As stated in the introduction the ultimate goal of the present project is to derive bolometric luminosities and masses of the low-luminosity YSOs. This will be dealt with in a forthcoming paper based on observations at additional wavelengths and theoretical modelling.

*Acknowledgements.* See Acknowledgements in Césarsky et al. this issue.

## References

André Ph., Montmerle T., 1994, ApJ 420, 837
Césarsky, C.J. et al., 1996, this issue
Feigelson E.D., Casanova S., Montmerle T., Guibert J., 1993, ApJ 416, 623
Gauvin L.S., Strom K.M., 1992, ApJ 385, 217
Graham J.A., Hartigan P., 1988, A&A 95, 1197
Hartigan P., 1993, AJ 105, 1511
Kenyon S.J., Hartmann L. 1995, ApJS 101, 117
Kessler, M. et al., 1996, this issue
Lawson, W.A., Feigelson, E.D., Huenemoerder, D.P. 1996, MNRAS 280, 1971
Mattila K., Liljeström T., Toriseva M., 1989, in "Low Mass Star Formation and Pre-Main Sequence Objects", ESO Conference and Workshop Proceedings No. 33, ed. Reipurth, B., p.153
Nelson L., Rappaport S., Joss P.C., 1993, ApJ 404, 723
Osterloh M., Beckwith S.V.W. 1995, ApJ 439, 288
Prusti T., Whittet D.C.B., Wesselius P.R., 1992, MNRAS 254, 361
Whittet D.C.B., Assendorp R., Prusti T., Roth M., Wesselius P.R., 1991 A&A 251, 524
Whittet D.C.B., 1988, in "Dust in the Universe", eds. Bailey M.E. & Williams D.A., p. 25

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.