AN EXTREMELY YOUNG EMBEDDED CLUSTER?

A.A. Kaas[1,2,3], G. Olofsson[2], S. Bontemps[2,4], P. André[5], L. Nordh[2], M. Huldtgren[2], T. Prusti[6], A. Abergel[7], F. Boulanger[7], M. Burgdorf[6], M.M. Casali[8], C.J. Cesarsky[5], J. Davies[9], E. Falgarone[10], T. Montmerle[5], M. Perault[10], P. Persi[11], J.L. Puget[7], and F. Sibille[12]

[1]Astrophysics Division of ESA, ESTEC, 2201 AZ Noordwijk, The Netherlands
[2]Stockholm Observatory, S-133 36 Saltsjöbaden, Sweden
[3]Visiting astronomer at Nordic Optical Telescope, La Palma
[4]Observatoire de Bordeaux, BP89, FR-33270 Floirac, France
[5]Service d'Astrophysique, CEA Saclay, 91191 Gif-sur-Yvette,France
[6]ISO/SOC, Astrophysics Division of ESA, Villafranca, Spain
[7]IAS, Université Paris XI, 91405 Orsay, France
[8]Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK
[9]Joint Astronomy Centre, 660 N. A'Ohoku Place, University Park, Hilo, HI 96720, USA
[10]ENS Radioastronomie, 24 Rue Lhomond, 75231 Paris, France
[11]IAS, CNR, v. E. Fermi 21, 00044 Frascati, Italy
[12]Observatoire de Lyon, 69230 Saint Genis Laval, France

Abstract

The Serpens Cloud Core is a relatively well studied region of low-mass star formation. An ISOCAM survey in the two broad band filters LW2 (5-8.5 μm) and LW3 (12-18 μm) provided, however, sufficient sensitivity and spatial resolution to investigate this embedded population in the mid-IR for the first time. From the single ISOCAM colour index [14.3/6.7], sources with mid-IR excesses are clearly separated from those without and assigned as bona-fide young stellar objects (YSOs). In combination with ground based near-IR imaging, the spectral energy distribution (SED) of the YSOs are sampled from about 1 to 18 μm. This allows us to use the IR spectral classification scheme, based on the shape of the SED in the mid-IR, to judge whether these YSOs are of type Class I (protostars) or Class II (T Tauri stars). The Class I/Class II number ratio is found to be exceptionally large compared to other star formation regions. Further, the spatial distribution of the Class I sources is found to be more concentrated along the NW-SE oriented ridge of the dense cloud, than that of the Class II sources. We find a tendency of sub-clustering on scales around 0.1 pc along the NW-SE ridge.

Key words: Stars: formation – Stars: pre-main-sequence –

1. Introduction

Young stellar clusters probably hold the clues to many unanswered questions about cloud fragmentation and the origin of the stellar initial mass function. In the youngest regions, where the stellar populations are still deeply embedded in their parental molecular cloud, we would expect to find some link between the stellar content and the cloud properties. From an observational point of view, however, obtaining a complete account of the stellar population in such regions is difficult due to cloud extinction. But with ISOCAM (Cesarsky et al. 1996), the camera aboard the Infrared Space Observatory (Kessler et al. 1996), the sensitivity and spatial resolution in the mid-infrared has been sufficient to identify and study a large number of new embedded YSOs in many nearby star formation regions.

In this paper we present ISOCAM results on the stellar content of the Serpens Cloud Core, one of the nearby young clusters (d=260pc, according to Straizys et al. 1996). This cluster shows several signs of active star formation, e.g. molecular outflows (Bally & Lada 1983; White et al. 1995; Huard et al. 1997; Herbst et al. 1997), pre-stellar condensations seen as submm sources (Casali et al. 1993; McMullin et al. 1994; Testi & Sargent 1998), as well as jets and knots in H_2 line emission (Eiroa et al. 1997; Herbst et al. 1997). It also contains especially interesting objects, such as a far-IR source possibly associated with a non-thermal triple radio continuum source (Rodriguez et al. 1989) and a deeply embedded FUor-like object (Hodapp et al. 1996). Hurt & Barsony (1996) suggested that Serpens might contain one of the richest known collections of Class 0 objects. The stellar content is well studied in the near-IR, and YSOs have been identified by properties such as near-IR excesses, association with nebulosities, and variability (Strom et al. 1976; Churchwell & Koornneef 1986; Eiroa & Casali 1992; Horrobin et al. 1997; Sogawa et al. 1997; Giovannetti et al. 1998; Kaas 1999). The Serpens Cloud Core is rather opaque in the optical, and therefore its stellar members have not been classified as classical or weak-lined T Tauri stars. Also, the spatial extent of this cluster is small and compact, such that for instance the IRAS data suffer from severe source confusion. Using ISOCAM photometry in combination with deep near-IR photometry, we now have better tools to identify and classify the YSO population. Here we show that the observed properties of the sample of YSOs we found, suggest an unusually young age for the region.

Proc. of 33rd ESLAB Symp. *"Star formation from the small to the large scale"* (F. Favata, A. A. Kaas & A. Wilson eds., ESA SP-445, 2000)

2. Observations

This study is based on ISOCAM observations in the two broad band filters LW2 (6.7 μm) and LW3 (14.3 μm), and deep near-IR imaging in the filters J (1.25 μm), H (1.65 μm), and K (2.2 μm). The near-IR observations were performed with the Arcetri Infrared Camera at the Nordic Optical Telescope, La Palma, about 4 months after the ISOCAM observations. This particular study concentrates on the $8' \times 6'$ field covered by both mid and near infrared imaging (see Fig. 1), and this is the region usually referred to as the Serpens Cloud Core. See Kaas et al. (2000) for detailed descriptions of observations and reductions, as well as general results of the ISOCAM survey in Serpens.

3. Results

One of the most important general results of the ISOCAM star formation surveys is that mid-IR excess sources are well separated from reddened field stars by the single colour index [14.3/6.7] in all nearby star formation regions studied (e.g. Nordh et al. 1996; Bontemps et al. 1998; Kaas et al. 1999; Olofsson et al. 1999; Persi et al. 2000). Thus, by their mid-IR excesses, many new young stellar objects (YSOs) have been identified in all regions. Typically, the known YSO populations were increased by a factor of about 2 in number. An ISOCAM colour magnitude diagram of the Serpens region is shown in Kaas et al. (1999).

In Fig. 1 we show the ISOCAM mosaic of the $13' \times 13'$ field "Serp CE", centred on the B1950 position 18:27:16 +01:14:00, from the LNORDH.SURVEY_1. In addition to these data, we have also used deeper images with better pixel resolution, available for parts of the region from GOLOFSSO.D_SURMC. All the brightest sources in this field are mid-IR excess sources (in the colour version these are coded red). For point source detection and photometry, not only the spatial, but also the temporal information in the data cubes was used.

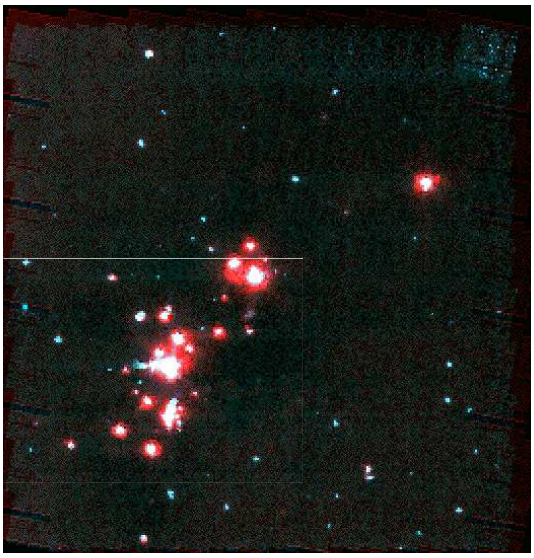

Figure 1. ISOCAM mosaic of the $13' \times 13'$ field containing the Serpens Cloud Core (mid-IR excess sources are coded red in the colour version). The region mapped in JHK is indicated.

For the sources where we have near-IR as well as mid-IR photometry, we can use the classical parametrization of the spectral energy distribution (SED) by the spectral index $\alpha = (d \log \lambda F_\lambda)/(d \log \lambda)$, i.e. the slope from the near- to the mid-IR (Adams et al. 1987; Lada 1987). Following this IR spectral classification scheme, we can distinguish the mid-IR excess YSOs in Class I and Class II sources. In this study we have calculated the following two SED indices: $\alpha_{2.2-6.7}$ and $\alpha_{2.2-14.3}$, which can be translated into the two colour indices $K - m_{6.7}$ and $K - m_{14.3}$ in terms of magnitudes. In Fig. 2 $\alpha_{2.2-6.7}$ is plotted versus $\alpha_{2.2-14.3}$ for the $8' \times 6'$ field. A normal stellar photosphere is expected to have $\alpha = -3$. Sources without IR excesses (open circles) are seen to outline the extinction vector in this diagram. Sources with mid-IR excesses (filled circles) fall along a slope similar to the extinction vector, but displaced to the right in the diagram. The locations of Class I and Class II sources are separated by the transition region around $\alpha = 0$ where the so-called flat-spectrum sources are found (cf. Greene et al. 1994). We have here used the $\alpha_{2.2-14.3}$ index to define the regions of these classes. The border between Class II and Class III sources is set at $\alpha = -1.6$, based on Andre & Montmerle (1994) and Greene et al. (1994). We note that no distinction can be made between Class III sources and field stars from our data. But X-ray data at sufficient spatial resolution and sensitivity is expected to be useful for this purpose, since X-rays are found to be a reliable tracer of YSOs in molecular clouds (Feigelson & Montmerle 1999).

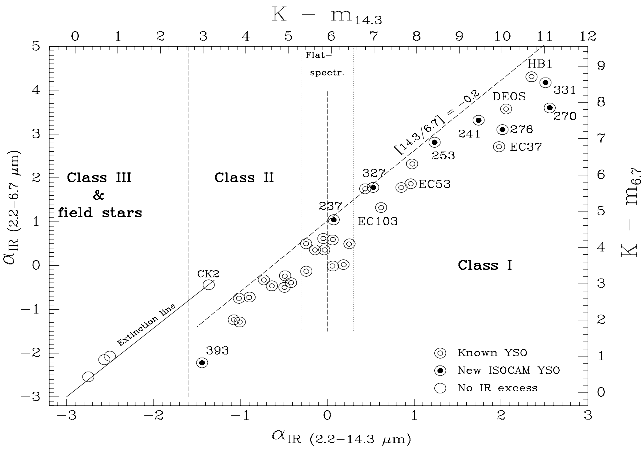

Figure 2. The IR spectral index $\alpha_{2.2-6.7}$ plotted versus the index $\alpha_{2.2-14.3}$, or in terms of magnitudes the $K - m_{6.7}/K - m_{14.3}$ colour diagram for the Serpens Cloud Core. Some of the YSOs in Fig. 3 have no 14.3 μm detection. These were classified from the $H - K/K - m_{6.7}$ diagram (see Kaas et al. 2000 for details).

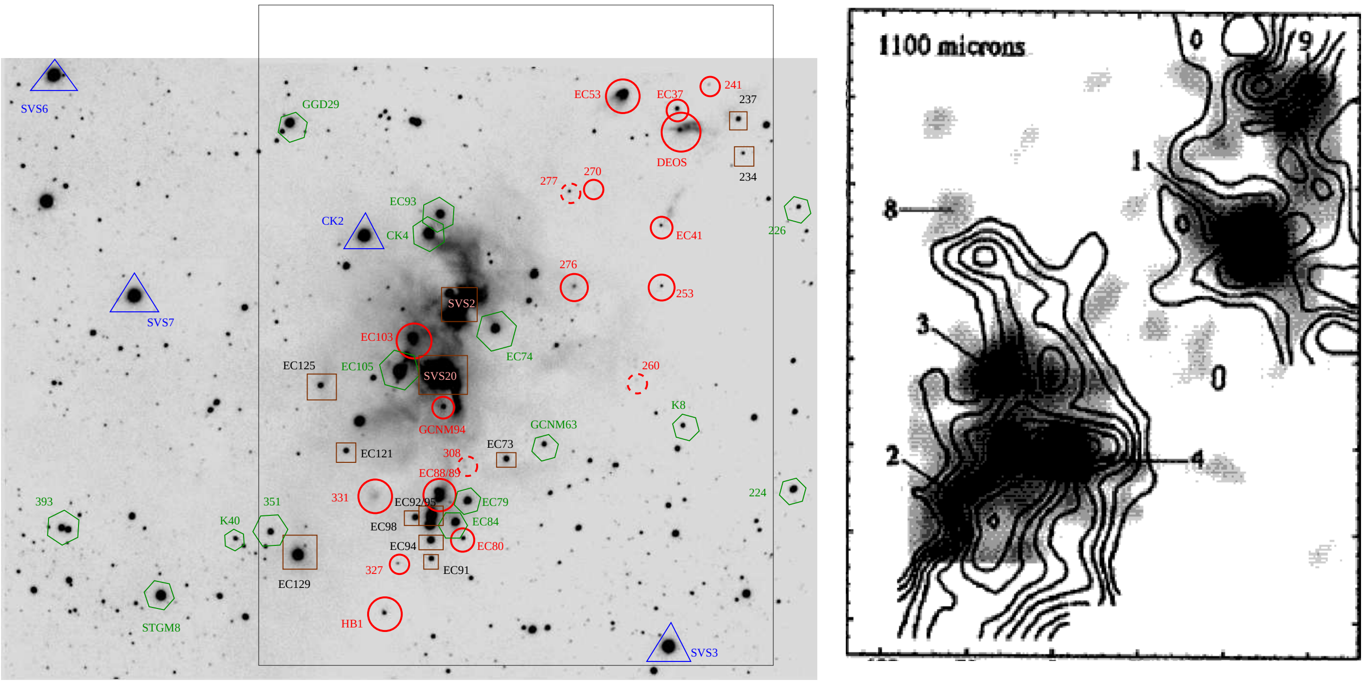

Figure 3. This figure shows to the left the spatial distribution of the Class I sources (circles), the "flat-spectrum" sources (squares), the Class II sources (hexagons), and sources without IR excesses (triangles) overlaid on a K band mosaic (Kaas 1999). Dashed circles indicate Class I sources defined from the $\alpha_{2.2-6.7}$ index when undetected at 14.3 μm. Symbol size is roughly proportional to the 6.7 μm brightness. The box outlines the area occupied by the figure to the right, which is reproduced from White, Casali & Eiroa (1995). It is a $C^{18}O$ map (contours from 8 K km s^{-1} in steps of 1 K km s^{-1}) overlaid on a 1100 μm continuum map in greyscale (see Casali, Eiroa & Duncan 1993 for quantitative information).

4. Discussion

4.1. Large fraction of Class I sources

The most surprising result from Fig. 2 is the large number of (14) sources in the Class I category ($\alpha_{2.2-14.3} > 0.3$) compared to the 10 Class IIs ($-1.6 < \alpha_{2.2-14.3} < -0.3$). In addition to these there are also 10 "flat-spectrum" sources. This is exceptional since Class II sources usually outnumber Class Is by typically 10 to 1 in most star formation regions. For instance, the samples of YSOs found in ρ Ophiuchi and Chamaeleon I have Class I/Class II number ratios between 0.1 and 0.2 (see Bontemps 2000; Olofsson et al. 2000), when defined according to the same spectral index $\alpha_{2.2-14.3}$. This apparently large population of Class I objects in Serpens would indeed be in line with a rich collection of Class 0 sources.

It should be emphasized, however, that the $\alpha_{2.2-14.3}$ index is not entirely reddening-independent. As an example, the most extinguished source *without* IR excess in Fig. 2 would wrongly fall in the Class II category. It is a reddened field star hidden behind about 60 magnitudes of visual extinction, and its lack of mid-IR excess prevents mis-classification. The alignment of YSOs parallel to the extinction slope, however, suggests that some of the Class Is could, in fact, be reddened Class II sources. In order to overcome the problem of reddening, we plotted $\alpha_{6.7-14.3}$ versus $\alpha_{2.2-14.3}$ and showed in Kaas et al. (1999) that if one also requires $\alpha_{6.7-14.3} > 0$ for a source to be truly Class I, then the Class I/Class II number ratio would reduce drastically. It seems, however, that the $\alpha_{6.7-14.3}$ index is quite sensitive to dust properties for such red sources, and cannot be used to reliably separate Class Is from Class IIs. The hypothesis that most of the Class Is could be deeply embedded Class IIs, also weakens for most sources when considering the mid-IR luminosities. As shown in Kaas et al. (2000), only a small fraction of the Class Is in Fig. 2 could possibly be highly extinguished Class IIs from a statistical point of view, since most of the Class Is are significantly brighter than most of the Class IIs in the mid-IR. Thus, while the exact value of the Class I/Class II number ratio might become subject to modification in the future, we believe that the main conclusion on the unusually large fraction of Class I sources will be maintained. Nevertheless, sufficient spatial resolution and sensitivity towards longer wavelengths, e.g. SIRTF (at 25 μm) and FIRST (90-250 μm), will be needed to understand the true nature of these sources.

One interpretation of the unusually large fraction of Class Is and Class 0s is that the Serpens Cloud Core is significantly younger than other nearby clusters. According to the simplified models of embedded clusters by Fletcher & Stahler (1994a; 1994b), the evolutionary phase where the number of protostars equals the number of PMS stars (adopting a constant mass accretion rate of 2 10^6 $M_\odot$ yr^{-1}), is at an age of only 10^5 yrs. While a discussion on the completeness limit of the ISOCAM sample of YSOs is given in Kaas et al. (2000), we here note that a number of faint YSOs, identified in previous near-IR studies (cf. Sect. 1), are undetected or unresolved by ISOCAM. Could these comprise part of the statistically "missing" Class II population? Whether this faint population is of a different nature than the brighter one, remains to be shown.

4.2. Spatial distributions

The spatial distributions of the different categories of sources from Fig. 2 are shown to the left in Fig. 3 overlaid on a K band image. In this figure the "flat-spectrum" sources are distinguished as a separate group. A box outlines the region shown to the right, which is a map of $C^{18}O$ (contours) overlaid on a map of 1100 μm continuum emission (greyscale) taken from White et al. (1995). There is a striking coincidence between the locations of the mid-IR excess sources and the tracers of the dense cloud (see also Fig. 1). In both cases the distribution is along a NW-SE oriented ridge. Further, sub-clustering along this ridge is seen as clumping in the distribution of the cloud tracers, as well as a concentration of YSOs in the corresponding regions.

It is also evident that the Class I and the "flat-spectrum" sources are spatially more confined to the NW-SE ridge than the Class II sources, which have a more scattered distribution. In particular the Class Is seem to form a set of 4 sub-clusters lined up along the ridge, having a size scale of about 0.1 pc (80-90$''$) on the average. Each of these sub-clusters contains between 2-6 Class I sources and between 5 and 14 YSOs in general. Since Class I sources are expected to be as young as a few 10^5 yrs, their positions should roughly indicate the place where they were born. A velocity dispersion as high as 1 km s^{-1} takes them only about 0.1 pc away from their site of formation.

5. Summary

We have used mid-IR (ISOCAM) photometry and deep near-IR (JHK) photometry to characterize the young stellar population in the Serpens Cloud Core. The large fraction of Class I sources could indicate a very young age for this embedded cluster. The Class I sources appear spatially more confined to the NW-SE oriented ridge of the cloud than the Class II sources, and we see a tendency for sub-clustering along this ridge at size scales of $\sim$ 0.1 pc.

Acknowledgements

Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with participation of ISAS and NASA. The Nordic Optical Telescope is operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias. Thanks to staff and to the Arnica team: C. Baffa, M. Sozzi, R. Stanga and L. Testi for support. The Swedish National Space Board is acknowledged.

References

Adams, F.C., Lada, C.J., Shu, F.H., 1987, ApJ 312, 788
André, P., Montmerle, T., 1994, ApJ 420, 837
Bally, J., Lada, C.J., 1983, ApJ 265, 824
Bontemps, S., Nordh, L., Olofsson, G., et al. 1998, In: Starformation with ISO, eds. Yun, J., Liseau, R., p. 141
Bontemps, S., 2000, these proceedings
Casali, M.M., Eiroa, C., Duncan, W.D., 1993, A&A 275, 195
Churchwell E., Koornneef J., 1986, ApJ 300, 729
Cesarsky C.J. et al., 1996, A&A 315, L32
Eiroa, C., Casali, M., 1992, A&A 262, 468
Eiroa, C., Palacios, J., Eislöffel, J., Casali, M.M., Curiel, S., 1997, In: Low Mass Star Formation - from infall to Outflow, eds. Malbet, F. & Castets, A., p. 103
Feigelson, E.D., Montmerle, T., 1999, ARA&A 37, 363
Fletcher, A.B., Stahler, S.W., 1994, ApJ 435, 313
Fletcher, A.B., Stahler, S.W., 1994, ApJ 435, 329
Giovannetti, P., Caux, E., Nadeau, D., Monin J.-L., 1998 A&A 330, 990
Greene, T.P., Wilking, B.A., André, P., Young, E.T., Lada, C.J., 1994, ApJ 434, 614
Herbst, T.M., Beckwith S.V.W., Robberto M., 1997, ApJ 486, L59
Hodapp, K.-W., Hora, J.L., Rayner, J.T., Pickles, A.J., Ladd, E.F., 1996, ApJ 468, 861
Horrobin, M.J., Casali, M.M., Eiroa, C., 1997, A&A 320, L41
Huard, T.L., Weintraub, D.A., Kastner, J.H., 1997, MNRAS 290, 598
Hurt, R.L. & Barsony, M., 1996, ApJL 460, 45
Kaas, A.A., 1999, AJ, 118, 558
Kaas, A.A., Olofsson, G., Bontemps, S. et al., 1999, In: The Universe as seen by ISO, ESA SP-427, p. 493
Kaas, A.A., Olofsson, G., Bontemps, S. et al., 2000, in prep
Kessler, M.F. et al., 1996, A&A, 315, L27
Lada, C.J., 1987, In: IAU Symp. 115, Star Forming Regions, eds. Peimbert, M. & Jugaku, J., p. 1
McMullin, J.P., Mundy, L., Wilking, B.A., Hezel, T., Blake, G.A., 1994, ApJ 424, 222
Nordh, L., Olofsson, G., Abergel, A. et al., 1996, A&A, 315, L185
Olofsson, G., Huldtgren, M., Kaas, A.A., Bontemps, S., Nordh, L., et al. 1999, A&A, 350, 883
Olofsson, G., Kaas, A.A., Bontemps, S., et al. 2000, these proceedings
Persi, P., Marenzi, A.R., Olofsson, G., et al. 2000, submitted to A&A
Rodriguez, L. F., Curiel, S., Moran, J. M., Mirabel, I. F., Roth, M., Garay, G., 1989, ApJ 346, L85
Sogawa, H., Tamura, M., Gatley, I., Merrill, K.M., 1997, AJ 113, 1057
Straižys, V., Černis, K, Bartašiūtė, S., 1996, Baltic Astronomy 5, 125
Strom, S.E., Vrba, F.J., Strom, K.M., 1976, AJ 81, 683
Testi, L., Sargent, A.I., 1998, ApJ 508, L91
White G.J., Casali M.M., Eiroa C., 1995, A&A 298, 594