Mem. S.A.It. Vol. 80, 67
© SAIt 2009

Memorie della

Infrared and optical studies of the Chamaeleon II and Lupus low-mass star forming regions

L. Spezzi[1,2], J.M. Alcalá[2], N. Chapman[3], E. Covino[2], N.J. Evans II[4], A. Frasca[1], D. Gandolfi[1], T.L. Huard[5], I. Oliveira[6], J.K. Jørgensen[7], B. Merín[8], and K.R. Stapelfeldt[9]

[1] INAF–OA Catania, Via S. Sofia 78, I-95123 Catania, Italy
e-mail: lspezzi@oact.inaf.it
[2] INAF–OA Capodimonte, Via Moiariello 16, I-80131 Naples, Italy
[3] Astronomy Department, University of Maryland, College Park, MD 20742
[4] Astronomy Department, University of Texas at Austin, 1 University Station C1400, Austin, TX 78712-0259
[5] SAO, 60 Garden Street, MS42, Cambridge, MA 02138
[6] Division of Geological and Planetary Sciences, CALTEC, Pasadena, CA 91125, USA
[7] Argelander-Institut für Astronomie, University of Bonn, Auf dem Hügel 71, 53121 Bonn, Germany
[8] ESA-ESTEC, Keplerlaan 1, PO Box 299, 2200 AG Noordwijk, The Netherlands
[9] Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands

Abstract.
The Spitzer Legacy survey "From Molecular Cores to Planet-forming Disks" (c2d Evans et al. 2003) provided infrared observations of sources that span the evolutionary sequence from molecular cores to proto-planetary disks, encompassing a wide range of star-forming environments. These overall observations allowed to study crucial steps in the formation of stars and planets with unprecedented sensitivity. We present some results from the Spitzer observations and complementary data in the low-mass star forming regions in Chamaeleon II and Lupus. We focus, in particular, on the star-formation history and activity of these clouds, the low-mass end of their IMF and the envelope/disk properties of their young populations.

Key words. Stars: formation – Stars: low-mass, brown dwarfs – Stars: pre-main sequence – Stars: circumstellar matter – Stars: protoplanetary disks

1. Introduction

The formation of low-mass stars and brown dwarfs (BDs) and their proto-planetary disks is a hot observational topic. The *Spitzer* Space Telescope (wavelength coverage 3-180μm; Gallagher et al. 2003) offers a unique opportunity for a major advance in this research. Because of the large obscuration of the pla-

Send offprint requests to: L. Spezzi

centary circumstellar disks at optical and near-IR wavelengths, the youngest protostars (i.e. IR Class 0 sources) are detected only at far-IR and millimeter wavelengths, while the more evolved protostars (i.e. IR Class I sources), which have less mass in the placentary envelope, have spectral energy distributions (SEDs) rising in the mid-IR, but decreasing at longer wavelengths. The *Spitzer* Legacy Survey *From Molecular Cores to Planet Forming Disks* or c2d (Evans et al. 2003) was aimed at studying the process of star and planet formation, from the earliest stages of molecular cores, up to the epoch of planet-forming disks. Chamaeleon II (Cha II) and the Lupus complex are among the five star forming regions included in the c2d Legacy survey. Because of their proximity to the Sun ($\approx$200 pc) and young age ($\lesssim$10 Myr), these clouds are particularly well-suited for studies of very young low-mass and sub-stellar objects.

In this contribution we summarize some of the results of the c2d observations in Cha II and Lupus which are reported in more detail in the c2d synthesis papers by Alcalá et al. (2008), Spezzi et al. (2008) and Merín et al. (2008).

2. Chamaeleon II

Based on Spitzer c2d IRAC and MIPS observations, complemented with optical imaging from WFI at ESO2.2m telescope (Spezzi et al. 2007) and spectroscopic follow-up data from FLAMES at ESO-VLT (Spezzi et al. 2008), we have performed a census of the pre-main sequence (PMS) population in Cha II (Fig.1). The population consists of 51 certified and 11 candidate PMS objects in about 1.75 square degrees. The census is complete down to M$\sim$0.03 $M_\odot$. The young nature of these objects is confirmed on the basis of the presence of infrared excess emission and typical spectral signatures of young low-mass stars, i.e. Lithium absorption and Hα emission superimposed in a late-type spectrum.

We studied the volume density of the 62 PMS objects and candidates with the following results: two tight groups, with volume densities higher than 25 $M_\odot$ pc^{-3}, can be identified but neither have enough members to qualify them as separate clusters. The spatial distribution of these groups is well correlated with the regions of high extinction as derived from the c2d extinction map. On the other hand, at 1 $M_\odot$ pc^{-3}, corresponding to the level proposed by Lada & Lada (2003) to define clusters, Cha II as a whole can be defined as a loose cluster. Most (75%) of the sources in Cha II are associated with this cluster, which also includes both tight sub-groups.

We characterise the sample of PMS objects by deriving their physical parameters. The vast majority of objects have masses M$\leq$1 $M_\odot$ and ages <6 Myr. Several of the PMS objects and candidates lie very close to or below the Hydrogen-burning limit. A first estimate of the slope of the IMF in Cha II is consistent with that of other T associations. The cloud mass determined from the extinction maps is on the order of 1000 $M_\odot$ and the SFE of 1-4% is similar to our estimates for other T associations like Taurus and Lupus, but significantly lower than for Cha I ($\sim$7%). This suggests that different star-formation activities in the Chamaeleon clouds may reflect a different history of star formation. The Cha II cloud turned about 7 $M_\odot$ into stars every Myr, i.e. less than the star formation rate in other star forming regions. At the level of the tight groups, the star formation rate and efficiency are much higher, but yet lower than in the other c2d clouds.

The analysis of the colours and SEDs shows that the Cha II population is dominated by objects with active accretion, with only a minority being systems with passive disks. The average PMS object in Cha II is the one for which the disk luminosity is about one third of the stellar luminosity. Most objects in Cha II possess typical SEDs corresponding to disks that evolve more or less homogeneously from flared to flat. The disk fraction in Cha II of 70-80% is exceptionally high in comparison with other star formation regions. If all the stars in Cha II were born with circumstellar disks, only a minor fraction of about 20-30% have lost their disks in about 2-3 Myr, i.e. the typical age of Cha II members. Such high disk fraction and the very small number of Class I sources relative to Class II sources may indicate that star formation in Chamaeleon has oc-

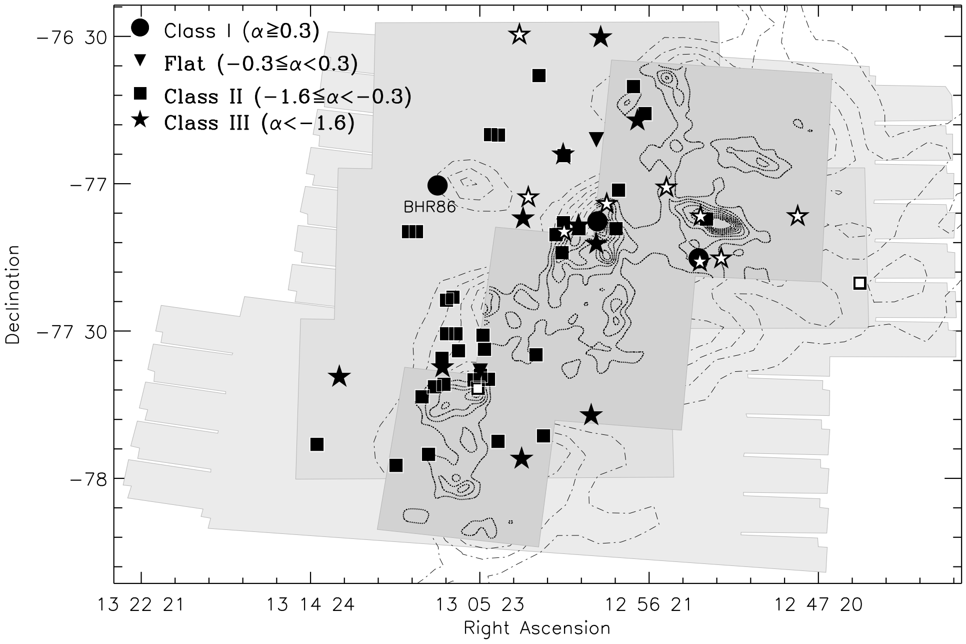

Fig. 1. Spatial distribution of the certified (filled symbols) and candidate (open symbols) PMS objects in Cha II as function of Lada Class, over-plotted on the contours from the c2d extinction map (continuous lines). The contour levels of extinction are from 2 mag to 20 mag, in steps of 2 mag. The shaded areas, from light to dark-grey, display the regions observed with MIPS, WFI and the IRAC 3.6-8 μm overlap, respectively. The dashed lines outside the IRAC area are the contour levels of extinction from Cambrésy (1999), from 1 mag to 6 mag in step of 0.35 mag. The higher resolution of the c2d extinction map with respect to the Cambrésy (1999) map can be appreciated.

curred rapidly a few million years ago. All the legitimate sub-stellar objects possess optically thick disks, confirming that disks are common down to the very low-mass regime, in agreement with previous findings in other regions of star formation. A trend for the optically thick disks to be more frequent in solar-mass stars is observed, but it is blurred by the poor statistics in Cha II.

3. Lupus

The Spitzer c2d observations in Lupus were concentrated on the three more active clouds of the complex, i.e. Lupus I, III and IV. IRAC and MIPS data from Spitzer, in combination with optical imaging data and follow-up spectroscopy, were used to provide a complete description of the three clouds and their young stellar populations, following the same scheme as described for Cha II (Sect. 2).

We performed a census of the young stellar objects applying the c2d Spitzer colour criteria (Harvey et al. 2007) in the three clouds and increase the number of cloud members by more than a factor of 4. The PMS population consists of 159 stars in the three clouds with infrared excess or spectroscopically determined membership, mostly found in the high density regions of the clouds and greatly dominated by low and very low-mass objects. The sample is complete down to M≈0.1 $M_\odot$ and probes well down into the sub-stellar regime.

A large majority of the young objects in Lupus are Class II or Class III objects, with only 20 (12%) of Class I or Flat spectrum sources. Objects of all classes appear equally distributed in the clouds and tend to cluster around the cloud high density peaks, except in Lupus IV where they do not follow the extinction distribution. The disk survey is complete down to debris-like systems in stars as small as M≈0.2 $M_\odot$ and includes sub-stellar objects with larger IR excesses. The disk fraction in Lupus is 70-80%, consistent with an age of 1-2 Myr. However, the young population contains 20% optically thick accretion disks and 40% relatively less flared disks regarding their Spitzer SEDs. A larger variety of inner disk structures is found for larger inner disk clearings, suggesting several possible evolutionary paths for the primordial disks. Similar disk masses are found for a range of inner disk clearings, which provides evidence against a clearing of the inner disks by photoevaporation.

Lupus I consist of a filamentary cloud structure with three density enhancements closely followed by early class objects. Lupus III contains a very active star-forming cluster with a very large number of objects of all classes. Lupus IV shows the highest extinction peak in Lupus with few late class objects away from the density peak. Clustering analysis of the PMS distribution recovers separate structures in the three clouds, with Lupus III being the most centrally populated and rich, followed by Lupus I and Lupus IV. Overall, the cloud structures are compatible with predictions from the hierarchical star formation scenario.

We estimate star formation efficiencies of a few percent and a star formation rate of 2-10 $M_\odot$ Myr^{-1} in the Lupus clouds. We also find a tentative linear correlation between the star formation efficiencies and the enclosed cloud masses of the three main stellar groups in Lupus.

Acknowledgements. This work was partially financed by the Istituto Nazionale di Astrofisica (INAF) through PRIN-INAF-2005. Support for this work, part of the Spitzer Legacy Science Program, was provided by NASA through contract 1224608 issued by the Jet Propulsion Laboratory, California Institute of Technology, under NASA contract 1407. We thank the c2d collaborators for the many discussions and suggestions. We are also grateful to many others, in particular to Salvatore Spezzi.

References

Alcalá, J. M., et al. 2008, ApJ, 676, 427
Allard, F., Hauschildt, P. H., & Schwenke, D. 2000, ApJ, 540, 1005
Cambrésy, L. 1999, A&A, 345, 965
Covey, K. R., Greene, T. P., Doppmann, G. W., Lada, C. J., & Wilking, B. A. 2005, Astronomische Nachrichten, 326, 886
D'Alessio, P., Merín, B., Calvet, N., Hartmann, L., & Montesinos, B. 2005, Revista Mexicana de Astronomia y Astrofisica, 41, 61
Dullemond, C. P., Dominik, C., & Natta, A. 2001, ApJ, 560, 957
Eislöffel, J., & Steinacker, J. 2008, 14th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun, 384, 359
Evans, N. J., II, et al. 2003, PASP, 115, 965
Gallagher, D. B., Irace, W. R., & Werner, M. W. 2003, Proc. SPIE, 4850, 17
Harvey, P., Merín, B., Huard, T. L., Rebull, L. M., Chapman, N., Evans, N. J., II, & Myers, P. C. 2007, ApJ, 663, 1149
Hauschildt, P. H., Allard, F., & Baron, E. 1999, ApJ, 512, 377
Lada, C. J., & Lada, E. A. 2003, ARA&A, 41, 57
Merín, B., et al. 2008, ApJS, 177, 551
Robitaille, T. P., Whitney, B. A., Indebetouw, R., Wood, K., & Denzmore, P. 2006, ApJS, 167, 256
Spezzi, L., Alcalá, J. M., Frasca, A., Covino, E., & Gandolfi, D. 2007, A&A, 470, 281
Spezzi, L., et al. 2008, ApJ, 680, 1295