RevMexAA (Serie de Conferencias), **29**, 43–47 (2007)

EMBEDDED CLUSTERS: LABORATORIES FOR STAR FORMATION

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RESUMEN

Los cúmulos embebidos son las unidades fundamentales de formación estelar en nuestra Galaxia, por tanto, es crítico estudiar sus propiedades para entender como transcurre la formación estelar tanto en la escala local como en la escala Galáctica. Hemos inspeccionado cúmulos embebidos en nubes moleculares locales con FLAMINGOS y estamos investigando las historias de formación estelar, la FIM, así como la estructura y evolución de estos cúmulos jóvenes. En esta presentación discutiré nuestros resultados para los cúmulos en los complejos de formación estelar en la Roseta y en Orión donde encontramos evidencia de evolución de la estructura de los cúmulos y variaciones de la funcion inicial de masa en el extremo de masas bajas.

ABSTRACT

Embedded clusters are the fundamental units of star formation in our Galaxy, therefore studying their properties is critical for understanding how star formation proceeds on both the local and Galactic scale. We have surveyed embedded clusters in local molecular clouds with FLAMINGOS and are investigating the star forming histories, IMF, structure and evolution of these young clusters. In this presentation, I will discuss our results for the clusters in the Rosette and Orion star forming complexes where we find evidence for the evolution of cluster structure and variations in the low mass end of the initial mass function.

Key Words: **STARS: FORMATION — STARS: LOW MASS, BROWN DWARFS**

1. INTRODUCTION

Observations of nearby giant molecular clouds (GMCs) have revealed that most stars form in densely packed embedded clusters. These clusters can be thought of as the fundamental units of star formation in our Galaxy. Consequently, it is important to study the properties of young embedded clusters in order to understand how star formation proceeds on both the local and Galactic scale. For example, determining quantities such as the embedded cluster mass function, cluster birthrate, cluster structure, the initial mass function (IMF) and global star formation efficiency allows us to investigate the origin and evolution of clusters, laying a foundation for understanding galaxy evolution. In this contribution, I briefly discuss the properties of embedded clusters and present a sample of results from our FLAMINGOS Survey of embedded clusters in nearby GMCs.

2. FLAMINGOS STAR FORMATION SURVEY

Through the National Optical Observatories (NOAO) Survey Program, we were granted ~ 200 nights of observing time using FLAMINGOS on the Kitt Peak 2.1 and 4 meter telescopes to obtain inventories of the star forming activity in local GMCs, including the Perseus, Orion, Monorcerous and the Rosette molecular cloud. FLAMINGOS, FLoridA Multi-Object Imaging Near-Infrared Grism Observatonal Spectrometer, was designed by Richard Elston (Elston, 1998) and built at the University of Florida. It is a wide field NIR imager and the world's first fully cryogenic NIR multi-object spectrometer. This combination offers us an unparalleled opportunity to study young embedded clusters. The primary goals of our survey are to identify the sites of recent star formation within the GMCs, and determine the distribution of star forming activity, embedded cluster properties, the star forming history and the shape and universality of the IMF.

As a result of the FLAMINGOS survey, we have identified over two-dozen embedded clusters and are studying their properties. For example, we imaged roughly 2 square degrees at J, H, and K, covering the majority of the molecular cloud and the Rosette Nebula (Figure 1). The Rosette Molecular complex at a distance of 1600pc is the most distant region in our survey (see Roman-Zuñiga & Lada 2007 for a review of this complex). We used the nearest-neighbor method on the sample of sources exhibiting near-infrared (JHK) excess emission to identify the clusters and study the distribution of star formation in the cloud. We have identified a total of 12 clusters in the Rosette Molecular Cloud Complex, including the

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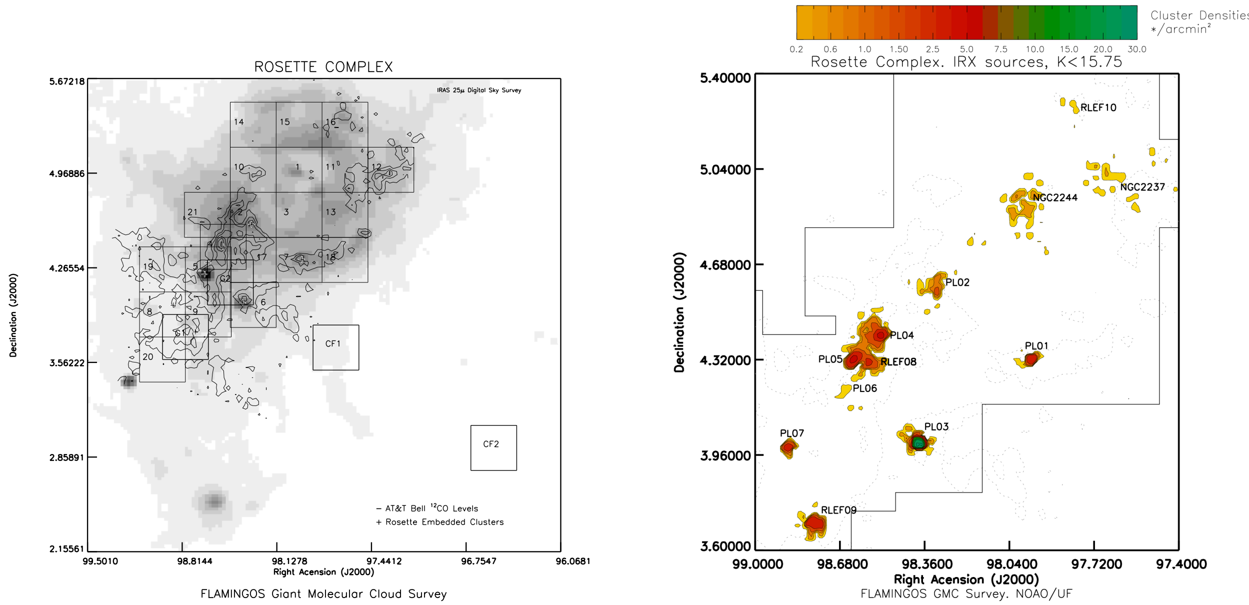

Fig. 1. FLAMINGOS Survey of the RMC. The figure on the left shows a map of the FLAMINGOS Survey of the Rosette Molecular Cloud. The boxes delimit individual FLAMINGOS fields ($20 \times 20'$) over an image of the IRAS 25μm emission in the region. Light solid contours represent the extension of the Rosette Molecular Cloud in CO emission from the survey of Blitz & Thaddeus (1980) in steps of 20.0K·km·s^{-1}. Crosses mark the centers of known embedded clusters from the previous study of Phelps & Lada (1997). The figure on the right shows the embedded clusters in the Rosette Complex. The colored scale contours indicate levels of surface density of infrared excess from nearest neighbor analysis. The dot line contours indicate levels of CO emission in steps of 20.0 K·km·s^{-1}, which define the extension of the main molecular cloud regions. The solid thin line indicates the limits of the FLAMINGOS survey coverage.

Rosette Nebula, the seven embedded clusters previously detected by Phelps & Lada (1997) and four new clusters (Roman-Zuñiga 2006; Roman-Zuñiga et al. 2007). The location of the clusters is shown in Figure 1. We determined that embedded clusters account for $\sim$ 85% of the star formation occurring within this molecular cloud, strengthening the conclusion that embedded clusters are the primary units of star formation in the Galaxy.

3. EMBEDDED CLUSTER PROPERTIES

An extensive and detailed review of embedded cluster properties can be found in Lada and Lada (2003). Embedded clusters have typical radii ranging from 0.3 to 1 pc. Masses range from 20 to 1000 solar masses with small clusters being more plentiful in number. Most stars appear to form in rich clusters that contain 100 or more members and have masses in excess of 50 $M_\odot$. Even though massive clusters ($M_\odot \sim 1000\ M_\odot$) are relatively rare, they are responsible for a significant fraction of the total stellar mass produced. Indeed, they contribute as much mass as the far more numerous, yet less massive counterparts.

Embedded clusters are characterized by high densities, with mean stellar densities ranging from 10 to 1000 $M_\odot$ pc^{-3}. Recently, Ferreira & Lada (2007) have investigated the morphologies of a sample of nearby (< 1Kpc) embedded clusters using the 2MASS database and an analysis technique based on the nearest-neighbor method. They find that 45% of embedded clusters are centrally condensed and less than 40% are circular indicating that a significant fraction of young clusters exhibit structure.

The embedded cluster birthrate has been found to be roughly an order of magnitude higher than the birthrate for classical open clusters. This suggests that most embedded clusters do not survive their emergence from molecular clouds but rather disperse to populate the Galactic field. Lada & Lada (2003) estimate that less than $\sim$ 4–7% of the clusters formed in molecular clouds are able to reach ages beyond 100 Myr in the solar neighborhood, and less than 10% survive longer than 10 Myr. Indeed, most clusters may dissolve well before they reach an age of 10 Myr.

We may be seeing the first evidence for rapid embedded cluster evolution in our study of the Rosette Complex. In this region, the sizes of the young clusters are found to increase with decreasing median extinction and decreasing near-infrared excess fraction (Figure 2, Roman-Zuñiga et al. 2007). It has been shown that the near-infrared excess fraction in young clusters decreases with the mean age of the cluster (e.g., Haisch, Lada, & Lada 2001). Therefore, in the Rosette, the smallest clusters appear to be the youngest and most deeply embedded whereas the largest clusters appear to be the oldest and have the least amount of extinction, possibly signaling their emergence from their parental cloud and initial expansion. Similar results are seen in our investigation of cluster structure using 2MASS (Ferreira & Lada 2007). In addition, we find that the degree of central condensation for the clusters decreases as a function of infrared excess fraction. Internal cluster structure appears to increase with age and this may be further evidence of the beginning of cluster expansion and disruption.

4. INITIAL MASS FUNCTION

Embedded clusters provide excellent laboratories for investigating the initial mass function (IMF), the origin of brown dwarfs, the origin and evolution of circumstellar disks and the likelihood of planet formation. Embedded clusters contain statistically significant numbers (hundreds) of young stellar objects, providing a meaningful sampling of essentially the entire stellar mass function. Clusters can be characterized by the median age of their members, which is a statistically reliable indicator of age, and a sample of clusters can be observed spanning a significantly wider range of age than is typical of stars formed in any individual star-forming region.

Investigations of the luminosity and mass functions of embedded clusters have found that the IMF exhibits a peak between 0.6 and 0.1 $M_\odot$, suggesting a characteristic mass associated with the star forming process. The form of the embedded cluster IMF is similar in shape to the IMF for open clusters and for field stars. Therefore, the IMF appears to be universal in its functional form throughout space and time. However, there is evidence that a universal IMF may not characterize all star forming events (Luhman 2000, 2006). In particular, our recent observations of the Orion Molecular Cloud Complex have suggested that the substellar IMF may be sensitive to environment. We have recently completed an extensive investigation of low mass star formation and brown dwarf formation in the L1630 Molecular cloud (Levine 2006; Levine et al. 2006; Levine & Lada 2007). We have obtained FLAMINGOS spectroscopy and photometry of over 200 stars in the three richest embedded clusters in this cloud, NGC 2024, NGC 2071 and NGC 2068. Figure 3 presents a sample of the classified M stars in the NGC 2024 cluster (Levine et al. 2006). We have derived the low mass IMF and brown dwarf abundances (Rss) for the three embedded clusters in L1630 and compared them to published brown dwarf abundances for the

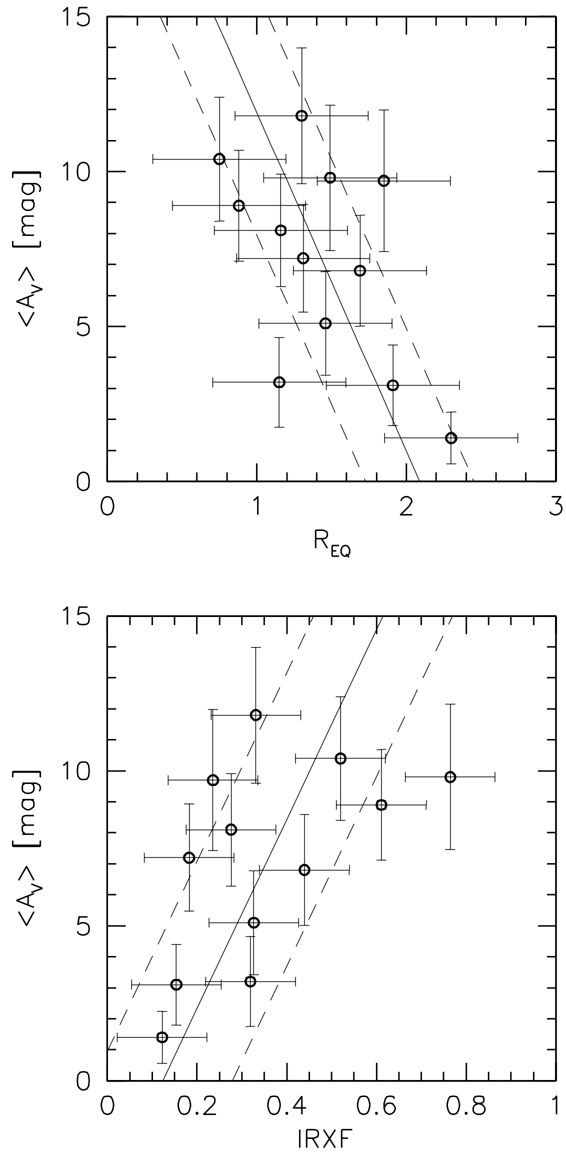

Fig. 2. Evolution of the Rosette Embedded Clusters. The top panel shows the size of the Rosette embedded clusters as a function of median extinction toward each cluster. The line and dotted lines represent a least squares linear fitting ±1 rms deviation. The bottom panel shows the relation between the near-infrared excess fraction ($K < 15.75$ mag) for the clustrs versus median extinction.

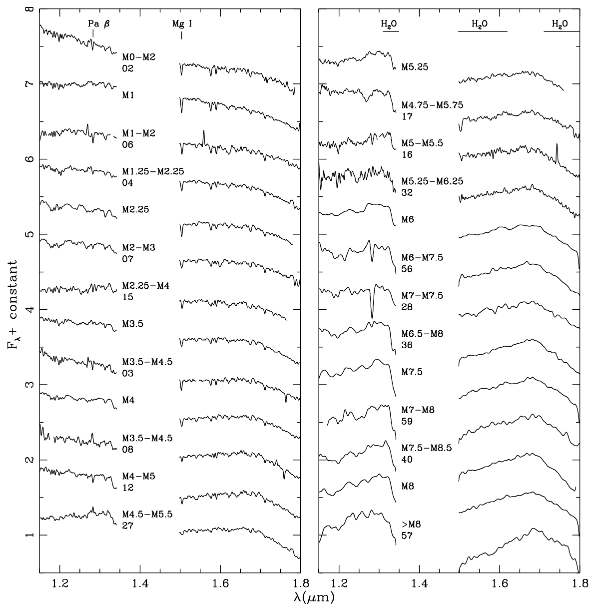

Fig. 3. Near-infrared spectra of a sample of M stars in the NGC 2024 Cluster. The specra were taken with FLAMINGOS on the 4 meter telescope on KPNO. Prominent spectral features are identified at the top. Objects having spectra types <M6 have been smoothed to R∼500 and objects ≥M6 have been smoothed to R∼200 to aid in the classification process. For details about the classification process see Levine et al. 2006.

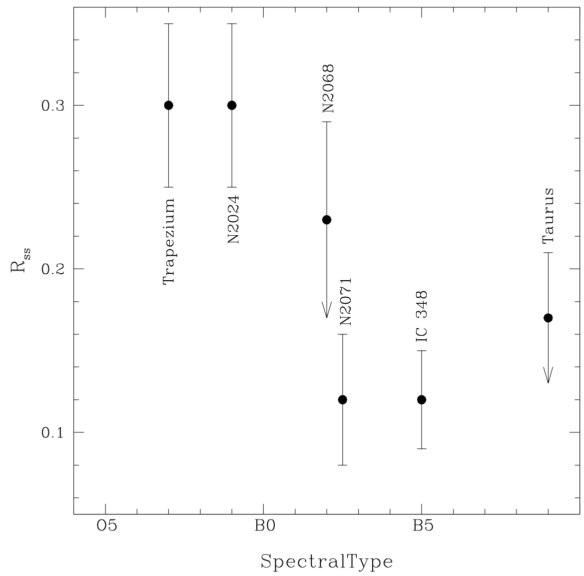

Fig. 4. R_{ss} versus spectral type of the most massive star for Taurus, IC 348, NGC 2024, NGC 2068, NGC2071 and the Trapezium.

IC 348 and Trapezium clusters and the Taurus star forming region (Luhman et al. 2003; Slesnick et al. 2004; Levine 2006; Luhman 2006; Guieu et al. 2006). The brown dwarf abundance appears to vary, with NGC 2024 and the Trapezium exhibiting signicantly higher abundances than NGC 2068, NGC 2071, IC 348 or Taurus. An investigation of the dependence of the Rss value on the local physical conditions in each star forming region indicates that the brown dwarf abundance may be a function of the spectral type (Figure 4) of the most massive star in the region and the gas density (Figure 5). These results suggest that the outcome of the brown dwarf formation process may be influenced by local star-forming conditions.

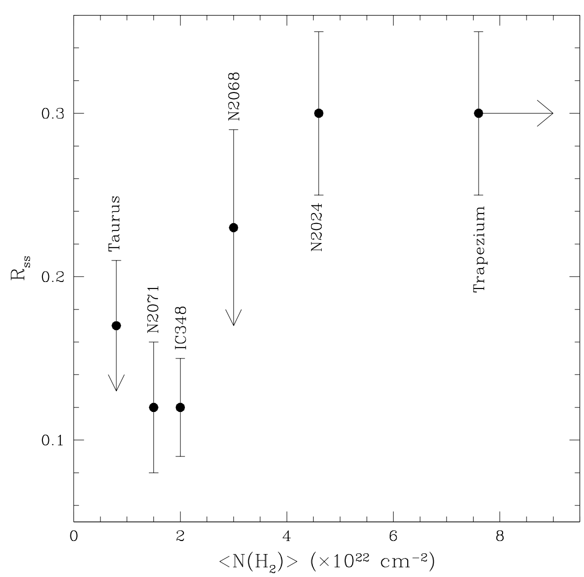

Fig. 5. R_{ss} versus gas density plotted for Taurus, IC 348, NGC 2024, NGC 2068, NGC 2071 and the Trapezium. The x-axis is the average column density of molecular hydrogen as inferred from the $C^{18}O$ data. The y-axis is the R_{ss} for each region as listed in Table 1 . Note that the value for the Trapezium is a lower limit.

5. EMBEDDED CLUSTER STUDIES WITH THE GTC

The GTC with state-of-the-art infrared instruments, such as EMIR and CIRCE opens a new parameter space for embedded cluster studies in our Galaxy. With these instruments, we will be able to observe clusters members members down to and below the hydrogen burning limit out to distances of 12 kpc. Consequently we will be able to obtain complete or nearly complete photometric and spectroscopic surveys of clusters over a large range of distances, thereby allowing the detailed investigation of the influence of environment on cluster origin and properties.

I would like to thank Joanna Levine and Carlos Roman-Zuñiga for their help with the figures. FLAMINGOS was designed and constructed by the IR instrumentation group (PI: R. Elston) at the University of Florida, Department of Astronomy with support from NSF grant (AST97-31180) and Kitt Peak National Observatory. The data presented were collected under the NOAO Survey Program, "Towards a Complete Near-Infrared Spectroscopic Survey of Giant Molecular Clouds" (PI: E. Lada) and supported by NSF grants, AST97-3367 and AST02-02976 and NASA LTSA NNG05GD66G to the University of Florida.

REFERENCES

Blitz, L., & Thaddeus, P. 1980, ApJ, 241, 676
Elston, R. 1998, Proc. SPIE, 3354, 404
Ferreira, B., & Lada, E. A. 2007, in preparation
Guieu, S., Dougados, C., Monin, J.-L., Magnier, E., & Martín, E. L. 2006, A&A, 446, 485
Haisch, K. E., Jr., Lada, E. A., & Lada, C. J. 2001, ApJ, 553, L153
Lada, C. J., & Lada, E. A. 2003, ARA&A, 41, 57
Levine, J. L. 2006, PhD Thesis, University of Florida
Levine, J. L., Steinhauer, A., Elston, R. J., & Lada, E. A. 2006, ApJ, 646, 1215
Levine, J. L., & Lada, E. A. 2007, in preparation
Luhman, K. L. 2000, ApJ, 544, 1044
Luhman, K. L., Stauffer, J. R., Muench, A. A., Rieke, G. H., Lada, E. A., Bouvier, J., & Lada, C. J. 2003, ApJ, 593, 1093
Luhman, K. L. 2006, ApJ, 645, 676
Phelps, R. L., & Lada, E. A. 1997, ApJ, 477, 176
Roman-Zuñiga, C. G. 2006, PhD Thesis, University of Flordia
Roman-Zuñiga, C., & Lada, E. A. 2007, in ASP Conf. Ser., The Handbook of Star Forming Regions, ed. B. Reipurth (San Francisco: ASP), in press
Roman-Zuñiga, C. Ferreria, B., Elston, R. J., & Lada, E. A. 2007, ApJ, submitted
Slesnick, C. L., Hillenbrand, L. A., & Carpenter, J. M. 2004, ApJ, 610, 1045