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Flamingos near-infrared study of the Serpens cloud

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Abstract. We present the results of a deep near-infrared imaging survey of the Serpens Cloud made with FLAMINGOS at the 2.1 m telescope at Kitt Peak National Observatory. We study the distribution of young embedded sources using the nearest neighbor method applied to a carefully selected sample of near-infrared excess (NIRX) stars that trace the latest episode of star formation in the complex. Our analysis finds the existence of six clusters, of which three are new in the molecular cloud. We determined a median age for the cluster to be 1-2 Myr at a mean distance of 300 pc.

Keywords : embedded star clusters: Serpens – NIR photometry – Spitzer – 2 mass

1. Introduction

Star formation is still one of the oldest and greatest mysteries in astrophysics. Stars form in molecular clouds, composed mainly of molecular hydrogen, which are the densest ($n > 10^3 \mathrm{cm}^{-3}$) and coldest ($T \approx 10^0 K$) components of the interstellar medium. A significant fraction of this molecular material exists in the form of large complexes called Giant Molecular Clouds (GMCs), with masses of $10^4 - 10^6 M_\odot$ and typical sizes of 10-100 pc.) GMCs are usually surrounded by extended envelopes of atomic hydrogen with typical masses of $10^6 M_\odot$. With the aid of infrared and millimeter-wave detectors developed in recent decades, we are now able to to see through the optically thick clouds where stars form, an impossible task for optical telescopes. This way we observe stars and even proto-stars while they are still embedded in their parental clouds. Surveys of molecular clouds indicate that 60% of young stars form in clusters (Carpenter 2000; Allen et al. 2007). It is therefore important to study star formation in clusters to understand the influence of the cluster environment in the process of star and planet formation. Of fundamental importance is the understanding of the spatial structure of clusters and of the evolution of that structure.

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As part of the NOAO survey program Toward a Complete Near-Infrared Spectroscopic and Imaging Survey of Giant Molecular Clouds (PI: E. A. Lada), the Serpens Molecular Cloud was observed. The Serpens is well-suited for studies of very young low-mass stars and sub-stellar objects because of its proximity (260 pc, Harvey et al. 2007a,b) and younger age (1-5 Myr, C. Eiroa, A. A. Djupvik & M. M. Casali 2008). The Spitzer Legacy Survey 'Molecular Cores to Planet Forming Disks' (c2d; Evans et al. 2003) in Serpens shows evidence of sequential star formation from SW to NE to the main Serpens Core (Kaas et al. 2004; Harvey et al. 2007a,b). The surface density of young stars in this region is much higher, by a factor of 10-100, than that of the other star-forming regions mapped by the c2d team (Evans et al. 2009). It is also an ideal region to build a 'template' sample for the study of disk evolution up to a few Myr within a single, small, well defined region by obtaining a complete, well defined sample of multi-wavelength observations of young stars and sub-stellar objects. Complementary Data also exist in X-ray to millimeter wavelengths, and spectroscopic follow-ups of the newly discovered population of young stars in Serpens. It is also the third star-forming region after Taurus and IC 348 for which such an unbiased dataset exists (Goodman 2004; Harvey et al. 2007; Enoch et al. 2007; Oliveira et al. 2009, 2010). Gorlova (2010) made a spectroscopic study of the Serpens core. The Serpens Main Cluster, known since mid 70s, is made of two compact protoclusters, lying in a 0.6 pc long filamentary structure, along NW-SE. The two sub-clusters have similar masses within similar sized regions ($\approx 30 M_{\odot}$ in 0.025 pc^2) each and an average age of 10^5 yr but differ in their velocity structures and molecular emission. The NW cluster is devoid of bright NIR sources, has outflows powered by deeply embedded class 0 and I protostars. A recent paper by Duarte-Cabral et al. (2011) infers that star formation has probably been triggered by the collision of two filament-like clouds.

2. Data and analysis

The Florida Multi-Object Imaging Near-Infrared Grism Observational Spectrometer (FLAMINGOS) obtained imaging data of the Serpens molecular cloud in JHK bands in October 2003 using seventeen $20' \times 20'$ fields tiled in the NESW direction with a plate scale of 0.6 arcsec pixel^{-1}, seeing of $1.5''$–$2.15''$ and airmass 1.2–2. Photometry for 1861 saturated sources brighter than $H = 11.5$ was replaced by 2MASS (Skrutskie et al. 2006). In this analysis, we only used catalog stars with photometric uncertainties deviating no more than 3σ from the mean. In addition, for those sources in which all three bands were required for the analysis, we placed a new limit to the total color uncertainties, $\sigma(J-H)$ and $\sigma(H-K) \leq 0.1$. Our catalog limits were finally 18.97, 17.62, & 17.33 mag in the J, H & K bands repectively. The total number of sources is 1,06,183. We cannot detect clusters using traditional star counts as the near infrared excess (NIRX) stars have a very high background contamination and non-uniform extinction due proximity to the galactic plane ($b = 5^0$). There are also other contaminants, such as, brown dwarfs, a variety of evolved stars, galaxies, and AGNs which lie in the region in the color-color plot where we expect to find YSOs. Hence, we adopt a two step optimized procedure to detect clusters (1) selecting them from a sample of NIRX stars and (2) analyzing their distribution of surface densities using a method of nearest neighbors (Roman-Zuniga et al. 2008). To reduce the scatter in the color-color plot, we use the following constraints: Magnitude: $5 \leq K \leq 16$ mag, Errors:$\sigma(J-H) < 0.2$, $\sigma(H-K) < 0.2$ for $K \leq 16.0$ and $\sigma(J-H) < 0.1$, $\sigma(H-K) < 0.1$ for $K \geq 16.0$ denoted by yellow points in Fig.1. The more reliable candidate YSO population from the NIRX sources are shown by black plus signs and satisfy the conditions: $J-H \leq 1.692(H-K)-0.1$ AND $J-H \geq 0.47(H-K)+0.46+0.1$ AND $H-K \geq 0.9$. The IR excess method used in order to detect YSOs misses YSOs that have already dispersed their circumstellar material. To obtain a total count of the cloud population, complementary methods such as association with nebulosities, X-rays, Radio, Imaging in H_α etc. and variability surveys that detect YSOs have to be used. It is important to note that these NIRX sources are only helping us to trace the location and rough extent of clusters with a photometric depth limit of $K \leq 15.75$, which is 1.5 mag deeper than 2 mass.

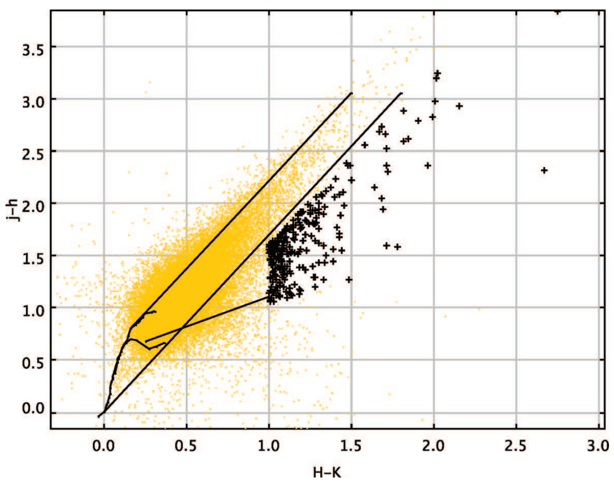

Figure 1. Color-color diagram of sources in Serpens.

We use the Nearest Neighbour (NN) Method (Casertano & Hut 1985) to optimize cluster identification using NIRX stars. For every NIRX star, we compute the jth NN surface density (μ_j) estimator for a star, given by, $\mu_j = \frac{j-1}{\pi * D_j^2}$ where D_j is the distance from any given star to its jth neighbor. We detected a total of 349 NIRX sources with $K \leq 15.75$. In Fig. 6 we show their distributions of 10th nearest neighbor (NN) distances, D_{10} and local surface densities, μ_{10}. The mean value of D_{10} is 6.0' (0.45 pc), which corresponds to a $\mu_{10} = 0.12$ stars arcmin^{-2} (0.92 stars pc^{-2}). Fig. 2 shows the NIRX sources (points) and the clusters (plus signs). Clusters are detected for stars where μ_j exceeds the mean density of 0.12 starsarcmin^{-2}. We identify 6 clusters, of which 3 are new. Once the clusters are identified, we study the complete sample of stars within the core radius of the density center. The Density Peak (Center) and the Core Radius are defined as follows: $X_j = \Sigma_i X_i \mu_j(i)/\mu_j(i)$ and $R_{core} = \Sigma_i |X_i -$

$X_{d,j}|\mu_j(i)/\Sigma\mu_j(i)$. We drew color-magnitude diagrams and color-color diagrams for the cluster regions and found the parameters for the clusters. Extinction can play a game of hide and seek, thus hiding existing clusters and revealing 'false' clusters. To test this we made extinction maps using NICER (Lombardi & Alves 2001) to confirm the detection of the clusters.

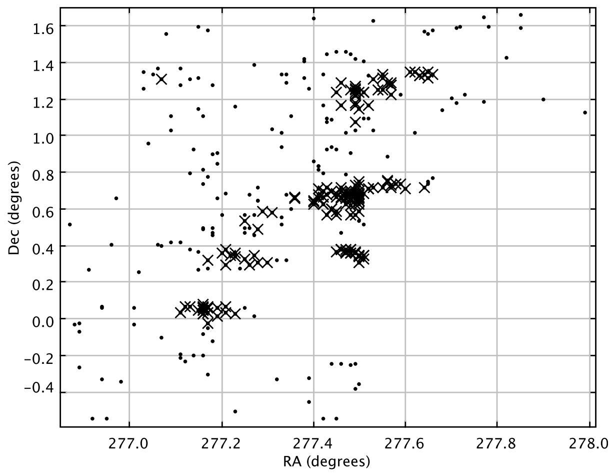

Figure 2. Distribution of clusters in the Serpens.

In conclusion, near infrared photometric data has been used to study star formation in the Serpens Cloud. Using the nearest neighbour method for a select sample of NIRX stars, we find six clusters, of which three are new. We determined a median age for the cluster to be 1-2 Myr at a mean distance of 300 pc. This is work in progress. A complete analysis of the Serpens will be published elsewhere. The author would like to thank her collaborators Carlos G. Roman-Zuniga and Elizabeth A. Lada for help and guidance.

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