A FLAMINGOS DEEP NEAR-INFRARED IMAGING SURVEY OF THE ROSETTE COMPLEX. I.
IDENTIFICATION AND DISTRIBUTION OF THE EMBEDDED POPULATION

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Received 2007 April 17; accepted 2007 September 17

ABSTRACT

We present the results of a deep near-infrared imaging survey of the Rosette complex made with FLAMINGOS at the 2.1 m telescope at Kitt Peak National Observatory. We studied the distribution of young embedded sources using a variation of 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 confirmed the existence of seven clusters previously detected in the molecular cloud, and identified four more clusters across the complex. We determined that 60% of the young stars in the complex and 86% of the stars within the molecular cloud are contained in clusters, implying that the majority of stars in the Rosette formed in embedded clusters. Also, half of the young embedded population is contained in four clusters that coincide with the central core of the cloud, where the main interaction with the H ii region is taking place. We compare the sizes, infrared excess fractions, and average extinction toward individual clusters to investigate their early evolution and expansion. In particular, the size and degree of central condensation within the clusters appear to be related to the degree of infrared excess and mean extinction in a way that suggests that the clusters form as compact entities and then quickly expand after formation. We found that the average infrared excess fraction of clusters increases as a function of distance from NGC 2244, implying a temporal sequence of star formation across the complex. This sequence appears to be primordial, possibly resulting from the formation and evolution of the molecular cloud and not from the interaction with the H ii region. Instead, the main influence of the H ii region could be to enhance or inhibit the underlying pattern of star formation in the cloud.

Subject headings: galaxies: star clusters — H ii regions — infrared: stars — ISM: clouds — stars: formation

Online material: color figures

1. INTRODUCTION

The study of the distribution of embedded stars in Giant Molecular Clouds (GMCs) is important for our understanding of the problem of star formation. At the embedded stage, these young stars represent the most recent episodes of star-forming activity, and therefore their physical properties should reflect the initial conditions of their parental cores. Near-infrared observations of the distribution of embedded stars in nearby clouds reveal that the majority of stars form in embedded clusters (Lada et al. 1991, hereafter LA91; Carpenter 2000, hereafter CA00) with rich clusters (>100 members) clearly dominating over small groups, as they contain more than 80% of the embedded stellar population in GMCs (Porras et al. 2003; Lada & Lada 2003, hereafter LL03). However, such surveys have been mostly restricted to nearby clouds (d < 500 pc), mainly because the study of more distant complexes is limited by photometric depth and resolution of the existing observations. Data from available surveys like the Two Micron All Sky Survey (2MASS) are not sensitive to faint sources (K > 14.3), limiting our ability to sample the young, low-mass population in distant molecular clouds. This makes it difficult to make meaningful comparisons between properties of star-forming regions in different parts of the Galaxy.

As part of the NOAO survey program Toward a Complete Near-Infrared Spectroscopic and Imaging Survey of Giant Molecular Clouds (PI: E. A. Lada), we chose the Rosette complex in the constellation of Monoceros for a new systematic near-infrared study of a molecular cloud outside of the local neighborhood. A complete review of past and current studies on the Rosette complex can be found in Román-Zúñiga & Lada (2008). The Rosette, located in the constellation of Monoceros at a distance of d = 1.6 ± 0.2 kpc (Park & Sung 2002; Hensberge et al. 2000), stands out as a very important astrophysical laboratory for the study of the early evolution of stars, because of its exquisite layout: at the center of its best-known feature, the Rosette Nebula, there is a giant OB association, NGC 2244, whose powerful UV radiation has generated an expanding H ii region. It has been suggested that the shock front generated by the photodissociation bubble could have triggered the formation of a family of young clusters (Phelps & Lada 1997, hereafter PL97) located in the adjacent, highly structured Rosette Molecular Cloud (RMC; e.g., Williams et al. 1995, hereafter WBS95), following a process known as sequential star formation (SSF; Elmegreen & Lada 1977). To test this hypothesis, it is crucial to investigate the influence of the local environment (particularly the expanding H ii region) on the properties of the young clusters, as it would help us to understand the different initial conditions under which cluster formation occurs.

The Rosette has been previously surveyed in the near-infrared. PL97 obtained J, H, and K photometry with the Simultaneous Quad Infrared Imaging Device (SQIID) at the KPNO 2.1 m telescope, and were able to identify seven embedded clusters by visual inspection of their images. In Figure 1 we show the location of the PL97 clusters2 in the RMC, in the context of the main regions of the cloud identified by Blitz & Thaddeus (1980): the regions A1-1 and A1-2, also known as the “ridge” and the “central core” of the cloud, host four of the PL97 clusters: PL02, PL04, PL05, and PL06. The cluster PL07 is located in region B or “back

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2 Hereafter we use the nomenclature “PL01”–“PL07” to refer to these clusters.
core” of the cloud. Finally, two more clusters, PL01 and PL03, are located in two cores apparently separated from the main cloud, labeled as D and G. All of the clusters discovered by PL97 were associated with a luminous IRAS source and a massive molecular clump from the study of WBS95, and until now, no other study has been able to determine the existence of additional clusters.

Recently, a spatially uniform catalog from the 2MASS survey was used by Li & Smith (2005) to study the distribution of star-forming activity in the RMC. They suggested the existence of three general areas of cluster formation, coincident with the areas with highest extinction and temperature of the cloud. The extensions of the star formation regions of Li & Smith were determined by eye, roughly tracing the division of Blitz & Thaddeus (1980) and enclosing the main clumps of WBS95 and the locations of the PL97 clusters. These general star-forming regions could not be compared with the clusters of PL97 because the extensions and membership of individual clusters were not determined in the later study. Also, due to the low sensitivity limits of 2MASS and SQUID (K < 14.2 mag), neither the study of PL97 nor that of Li & Smith could adequately sample the low-mass population at the distance of the Rosette complex and therefore could not determine the fraction of stars forming in clusters. Furthermore, the Rosette complex is located at a low Galactic latitude (b ≈ −1.8), and the level of field star contamination in the direction of the cloud is very high, making the identification of cloud members even more difficult, especially for low-sensitivity data.

In our study we try to overcome these problems by (1) using deeper observations of the region, capable of detecting sources below the limits previously set by 2MASS; (2) using a selected sample of sources with near-infrared excess (NIRX) to trace young populations with a minimum of nonmember contamination (e.g., Li et al. 1997); and (3) using the method of nearest neighbors (Casertano & Hut 1985, hereafter CH85) to detect surface densities intrinsically larger than the highly crowded field, thus allowing us to detect clusters of embedded stars.

The main goals of our survey are to investigate the distribution of star formation in the Rosette, determine the fraction of stars that form in embedded clusters, and compare these results to those found in other local clouds such as Orion. We also determine the distribution of the physical properties (i.e., size and NIRX fraction) of the identified clusters in order to study the star-forming history and evolution of the clusters. Finally, we aim to investigate the distribution of embedded sources across the cloud to investigate the influence of the H II region on its star-forming properties, and also to test the hypothesis of sequential formation.

The paper is organized as follows: in § 2 we describe our observations and the quality of our data set; in § 3 we explain the methods used to determine the distribution of young stars in the Rosette complex, specifically the selection of NIRX sources and the use of the nearest neighbor method; in § 4 we present the results from our analysis, namely the identification and properties of the embedded clusters; and in § 5 we discuss the implications of our results in the context of the global properties of the Rosette complex along with a summary of our work.

2. OBSERVATIONS AND DATA QUALITY ASSESSMENT

The data were obtained with the Florida Multi-Object Imaging Near-Infrared Grism Observational Spectrometer (FLAMINGOS) at the KPNO 2.1 m telescope. This project is part of the NOAO survey program Toward a Complete Near-Infrared Spectroscopic and Imaging Survey of Giant Molecular Clouds. At the 2.1 m telescope, FLAMINGOS has a field of view of 20' × 20', and in the case of the Rosette complex, a total of 23 FLAMINGOS fields were observed during winters of 2001–2004 using the J, H, and K filters (1.25, 1.65, and 2.2 μm, respectively). The Rosette observations were designed to survey the regions of significant molecular gas density revealed by the 12CO and 13CO maps of Blitz & Stark (1986; see also WBS95) (integrated intensity levels above 20 and 0.8 K km s−1, respectively) as well as the 25 μm emission map from the IRAS survey (we considered as significant those areas with emission above 5.0 MJy sr−1). The result is a very complete coverage of the Rosette Nebula and the RMC regions. A map showing the positions of the observed fields can be seen in Figure 2. Twenty of the fields are adjacent, while three of them (areas 4, G1, and G2) were added to enhance the quality of the observations in some particularly interesting regions. In addition, to account for the field contamination, we observed two near control fields located away from the main molecular cloud emission. These control fields have the same depth as any of our on-source fields, and their locations are also indicated in Figure 2.

All the data of the FLAMINGOS star formation survey were processed with the aid of pipelines built in the standard IRAF command language. One pipeline (see Román-Zúñiga 2006) processes raw data by applying a linearization correction, subtracting dark current, dividing by dome flat fields, applying a two-pass sky-subtraction method, and combining reduced frames into image products that are free of geometric distortions, resampled to twice their size, and trimmed into final frames of 4096 × 4096 pixels. These products were then analyzed with a second pipeline (see Levine 2007), which extracts all possible sources from a given field, applies point-spread function (PSF) photometry, and calculates an accurate astrometric solution and creates final catalogs after matching lists from individual filter observations. Both photometry and astrometry are calibrated with respect to 2MASS.

For the Rosette survey, the completeness limits are K = 17.25, H = 18.00, and J = 18.50 mag, and are slightly fainter in a few fields observed under optimal weather conditions. The completeness limits were determined with artificial star experiments, and apply well within 75%–80% of the area covered in each field, but are up to 0.25 mag brighter near the edges of the fields, where
the photometric sensitivity of the FLAMINGOS detector degraded from the center due to a loss in optical quality (E. A. Lada et al. 2008, in preparation). This optical degradation also affected the shapes of the star images near the edges, and we applied a correction to the zero point of the photometric calibration. The correction is radial, with the center on the point of best PSF adjustment (which varied, depending on field and epoch within a radius of approximately 100 pixels from position [3000, 2400] in the 4096 x 4096 final image grid), and for the Rosette survey fields it was well defined with a sixth-order polynomial form. Those stars located at radii where the correction was larger than 0.1 mag were not included in the final catalogs. In Figure 3 we show a map of the individual fields and the extension of the bad quality areas, which in all cases were smaller than 12%. The zero-point correction, however, helped to reduce photometric scatter in the acceptable areas by an average of 0.02 mag in each field. Our final mean photometric uncertainties are 0.058 / C6 0.012, 0.064 / C6 0.018, and 0.056 / C6 0.014 for J, H, and K, respectively.

Figure 4 shows the mean photometric uncertainties and their standard deviations per magnitude bin as a function of brightness in each band. In this analysis we only used catalog stars with photometric uncertainties deviating no more than 3.0 / C27 from the mean. Completeness limits for the analysis were not significantly compromised with these cuts, because most of the sources rejected for having large photometric uncertainties were fainter than J = 18.50, H = 18.25, and K = 17.50 mag. 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, \( \sigma_{\text{J-H}} = (\sigma_J^2 + \sigma_H^2)^{1/2} \) and \( \sigma_{\text{H-K}} = (\sigma_H^2 + \sigma_K^2)^{1/2} \), requiring them to be smaller than 0.1 mag. This last constraint restricted the photometric errors in each band to be no larger than 0.071 mag.

Sources brighter than approximately 11.0 mag suffered saturation. To account for this, we rejected all sources above \( H = 11.0 \) from our catalogs (this cut also removed saturated stars in bands J and K, which had slightly brighter saturation limits) and replaced them with the corresponding 2MASS point sources obtained from the All-Sky Release database. The total number of sources replaced was 798. After applying the photometric quality cuts to the entire database we retained 74,285 sources for analysis.

3. ANALYSIS

The Rosette complex is located at 1.6 kpc from the Sun, more than 4 times farther away than regions such as Orion and Perseus.

Fig. 3.—Extension of the areas of acceptable optical distortion, marked for each field as circles with radii equal to the center of the maximum bin at which the polynomial correction to the zero points (see text and Fig. 5) can be applied within the detector. This effect varies by field (size of the acceptable area) and filter: the solid, dotted, and dashed-line circles represent the tolerance radii for J, H, and K, respectively.

Fig. 4.—Intrinsic quality of the RMC survey. The points mark the mean value of the photometric error in a given magnitude bin, with the size of 1 standard deviation indicated by the error bars. The horizontal dashed lines mark the zero level and the sensitivity level, estimated at 0.1 mag. Vertical dotted lines indicate the sensitivity limits, marked as the bin at which the fiducial curve generated by the mean values crosses the 0.1 line. The dash-dotted line represents the 3 \( \sigma \) level of the fiducial errors; any star in our catalog with errors higher than these levels were rejected from the analysis.
where systematic searches for embedded clusters have been previously performed. Furthermore, the Rosette is located at a very low Galactic latitude ($b = -2$) and toward the antecenter of the Galaxy ($l = 210$), which results in a very high density of field sources located in the foreground and background of the cloud. These characteristics make it more difficult to detect clusters using traditional star count methods. For that reason, our analysis focuses on optimizing the detection of young, embedded sources in the cloud. This is done by (1) selecting them from a sample of NIRX stars and (2) analyzing their distribution of surface densities using a method of nearest neighbors.

### 3.1. Infrared Excess Stars

In the $J - H$ versus $H - K$ color-color diagram, NIRX stars fall to the right of the band defined by the projection of the giant and dwarf sequences along the direction of interstellar reddening. This vector of extinction is defined by a standard reddening law (e.g., Cohen et al. 1981; Rieke & Lebofsky 1985). If dereddened, low-mass NIRX stars would fall back to the classical T Tauri star (CTTS) locus (Meyer et al. 1997), which is defined by large $H - K$ colors indicative of dramatic intrinsic extinction due to the presence of circumstellar material. The fraction of stars falling into this NIRX region has been observed to be fairly large in deeply embedded clusters (e.g., Lada et al. 1996; Carpenter et al. 1997).

Studies have shown that the total NIRX fraction in young clusters decreases with age, as a result of inner disk evolution (Haisch et al. 2001). For example, the $JHK$ fraction in the Trapezium and NGC 2024 (ages $\sim 1$ Myr) is close to 50%, while in slightly older clusters like IC 348 (age $\sim 2$ Myr) the $JHK$ fraction is around 20%. The deeply embedded population of the RMC can be expected to be younger than the exposed OB association NGC 2244, which is estimated to have an age of 2 Myr from spectroscopic observations (Pérez et al. 1989; Park & Sung 2002). Thus, the $JHK$ excess fraction in the embedded clusters of the Rosette can be expected to be between 20% and 50%, significant enough to trace well the most recent episode of formation.

For our study, we define an NIRX star as one with colors that place it 0.1 mag (5 times the standard deviation of the $H - K$ uncertainty) to the right of the dwarf zero-age main sequence reddening band (ZAMSRB), and above $J - H = 0.47(H - K) + 0.46$, which defines the lower limit for the CTTS locus given the listed uncertainties of Meyer et al. (1997). The first of these two constraints avoids contamination of the sample from non-NIRX stars with large $H - K$ uncertainties that could place the stars slightly outside the right edge of the ZAMSRB. The second one impedes the inclusion of objects that lie in the region located below the CTTS line. This region, just as the one to the left of the ZAMSRB, contains detections that are mainly due to high color scatter. Also, in some cases unresolved galaxies (which can pass as stars) with large photometric spreads (Labbe et al. 2003) or highly inclined intrinsic reddening vectors—due to dominant emission from H II regions and AO stars (Héraudeau et al. 1996)—are located in this region of the diagram.

Combined effects of variable seeing quality over the seasons and variability of the focus quality across the wide detector field of FLAMINGOS, resulted in a high dispersion of color values at the faint end of our sample, and it cannot be reduced with the zero-point corrections or with the uncertainty restrictions. The scatter in the $H - K$ colors increases for sources fainter than $K = 15.75$ mag. At this limit, the field object density also increases significantly, and the larger the uncertainty in $H - K$, the more difficult it is to distinguish cloud members from background sources. In Figure 5 we show the color-color diagrams for stars with $K < 15.75$ mag and for stars with $15.75$ mag $< K < 17.25$ mag, respectively. In these diagrams, the lowest contour level shown represents the mean surface density of objects in the color-color space, and each subsequent level represents a step of 1 standard deviation. The diagrams show how the scatter for the bright end of the sample is much smaller than for the faint end, where we can see a quasi-symmetric increase in the dispersion of colors at both sides of the ZAMSRB near the most populated areas of the diagram. Our calculations indicate that the mean standard deviation of the $H - K$ color dispersion is twice as large for the faint-end bins (0.11 vs. 0.21 mag, calculated for the entire catalog). The effect is also slightly worse for those fields in the survey that were observed under the less favorable weather and air-mass conditions.
Large scatter in photometric colors directly affects the calculation of the number of NIRX stars in our survey. We performed a series of Monte Carlo experiments in which we simulated the colors of stars drawn from a model population with an age of 1 Myr (D’Antona & Mazzitelli 1994) located at the distance of the Rosette. We then added color errors and extinction to these sources, similar to those observed in the survey fields. We found that the number of stars with colors similar to those of NIRX stars due to photometric scatter can be up to 5 times larger for stars fainter than \( K = 15.75 \).

Because we are basing our analysis on the detection of infrared excess sources, we limited the primary aspect of our analysis, the identification of embedded clusters, to those stars in the bright end of the sample (\( K < 15.75 \) mag). This sample restriction is rather conservative, but assures a more robust detection across the entire survey area. It is important to remark that these bright NIRX sources are only helping us to trace the location and rough extension of clusters, and although our color uncertainties are high, individual \( K \)-band magnitudes are still good within 0.05 mag (averaged), and thus the sample is still robust enough to construct accurate luminosity distributions with a bin resolution of 0.25 mag. Also, the photometric depth limit of \( K = 15.75 \) implies a sample 1.5 mag deeper than 2MASS and is equivalent (for dwarf-type stars) to a stellar mass range of 0.09–0.18 \( M_\odot \)—for a population of 1 Myr embedded in a cloud with a typical extinction of 0–10 visual magnitudes (D’Antona & Mazzitelli 1994).

### 3.2. The Nearest Neighbor Method

In order to optimize cluster identification, we used a variation of the nearest neighbors method (NNM; CH85) to determine which objects in our fields have surface densities above the crowded background levels. The NNM has been shown to have success in detecting and outlining the extensions of embedded clusters (Nakajima et al. 1998; Gutermuth et al. 2005; B. Ferreira & E. A. Lada 2008, in preparation [hereafter FL08]). The generalized form of the \( j \)th NN surface density estimator for a star in a field is simply

\[
\mu_j = \frac{j - 1}{\pi D_j^2},
\]

where \( D_j \) is the distance from any given star to its \( j \)th neighbor. This estimator has only 1 degree of freedom, the fixed number of neighbors, \( j \), used to calculate the local density. For a large enough value of \( j \), the fluctuations in the local density estimations due to local irregularities will be small, which assures an accurate determination of the extension and structure of large systems. However, for the same reason, \( j \) also limits the minimum number of grouped stars that can be detected without confusion: if \( j \) is much larger than the minimum number of stars that define a group or cluster, then small structures could be overlooked, as their surface densities will be systematically lower than a defined average value. CH85 showed that \( j = 6 \) is the minimum number that can assure unbiased detection of groups with up to 1000 stars, but is 15% more susceptible to local statistical fluctuations than larger values of \( j \). The selection of \( j \) for each application will simply depend on the goal: for example, in their study of young clusters using 2MASS data, FL08 chose a \( j = 20 \) estimator, which allowed them to identify clusters with radii as small as 0.3 pc and a minimum of 20 ± 5 members. Gutermuth et al. (2005) used \( j = 5 \) to determine the membership in cluster fields at high resolution in combination with carefully corrected source counts.

At first, we tried to emulate FL08 by applying a \( j = 20 \) estimator to our final RMC catalog and our control fields, expecting to be able to detect and delimit the already known structures: NGC 2244 and the seven embedded clusters reported by PL97. The result was that NGC 2244 could be easily identified as a high-density region, along with the clusters PL04 and PL05, located in the core of the cloud. The three midsize clusters PL01, PL03, and PL07 could be identified too, but their apparent structures were not much more significant than some density fluctuations in our fields due to patchy extinction. Finally, stars in the smaller clusters PL02 and PL06 had 20th NN densities below the 3 \( \sigma \) level, and thus these clusters could not stand out above the noise levels of the distribution.

Cluster PL06, which is associated with the B-type protobinary AFGL 961, contains large quantities of obscuring material near its center, complicating the detection of its faintest and most embedded members even in carefully constructed near-infrared maps (e.g., Aspin 1998). Cluster PL02 is deeply embedded near the front part of the cloud, where material appears to be in contact with the expanding \( H \alpha \) region. Likely, for small embedded clusters like PL02 and PL06, the combination of small number of members, high background contamination, and nonuniform extinction hampers the effectiveness of the NNM. Furthermore, in regions of high extinction, some embedded clusters could have surface densities intrinsically lower than the field so that their members could be undetectable with a large \( j \). Or, random patches of low extinction in the cloud could have larger than average field densities and may pass as “false” clusters.

In order to overcome these complications, we applied the NNM only to a \( JHK \) color-selected sample of sources that exhibited a NIRX. This allowed us to trace preferentially the youngest and most probable members of the cloud. For this reason, the number of NIRX sources is expected to greatly diminish outside the molecular cloud, and therefore background contamination is reduced, along with false cluster occurrences. Also, the number of young sources with NIRX is expected to be larger in deeply embedded populations, and consequently high-extinction regions could actually present larger NIRX densities, opposite from the “all-star count” case, in which these regions would be overlooked.

Since it is expected that only a fraction of the members in a given young cluster exhibit infrared excess, our sample will diminish in size, and our \( j \) estimator value has to be reduced accordingly. We experimented with different values of \( j \), from 6 to 15, and we ultimately adopted a value of \( j = 10 \) for our analysis. This choice allows us to detect NIRX groups of 10 members, which for a typical NIRX fraction of 30\% (see §3.1) would trace a cluster with \( \sim 30 \) members. A preliminary visual inspection of the images of the less populated clusters, PL01, PL02, and PL06, indicated that the typical number of stars within visible areas of bright nebulousity—usually coincident with embedded cluster cores—could be, indeed, around 30. This is close to the minimum number that defines a cluster dynamically (Adams & Myers 2001; Lada & Lada 2003), and below that, any groups could at most be considered associations or isolated populations, although they will be harder to distinguish from local fluctuations. In principle, a lower value of \( j \) would allow us to detect those smaller stellar groups, but our tests indicate that analysis with lower values (i.e., \( j = 6–10 \)) do not differ significantly from the case of \( j = 10 \), and thus we opted for this, more robust, choice.

### 3.3. Nearest Neighbor Analysis for Infrared Excess Stars

We detected a total of 1169 \( \pm 34 \) NIRX sources with \( K < 15.75 \). In Figure 6 we show their distributions of 10th nearest neighbor (NN) distances, \( D_{10} \) and local surface densities, \( \mu_{10} \). The mean value of \( D_{10} \) is 3.79 (1.83 pc), which corresponds to a \( \mu_{10} = 0.2 \) stars arcmin\(^{-2} \) (0.92 stars pc\(^{-2} \)). This limit is also indicated in the plot.
CO from the study of Blitz & Stark (1986). From now on we will use the nomenclature of the main RMC features from Blitz & Thaddeus (1980). As seen in the figure, most NIRX stars with high NN densities are located within the molecular cloud, except for those located in the field of the Rosette Nebula.

In Figure 8 we show a contour level map of the local surface densities calculated with the NN method \((j = 10)\). The contours were constructed using a Nyquist sampling box of \(90^\circ\). Using this map, we define an embedded cluster as a region for which we can observe a closed contour at a level of 0.2 stars arcmin\(^{-2}\), containing at least 10 NIRX sources. Using this definition we found, in addition to NGC 2244 and the seven clusters from PL97, four additional areas that arise as significant but have not been previously studied:

1. The first new cluster, REFL08, is located in the central core of the cloud, east of cluster PL05 and south of cluster PL04. These two large neighbor clusters present patchy reddening and have a number of members already visible in optical plates (e.g., Digitized Sky Survey); thus, they can be considered to be partially emerged from the cloud. In contrast, REFL08 is not visible in any optical plates and has a large number of conspicuously reddened sources. Therefore, REFL08 appears to be a third, more deeply embedded substructure in this active region of star formation at the center of the cloud, in which clusters PL04 and PL05 are the largest clusters.

2. The second new cluster, REFL09, is a relatively extended, highly reddened cluster located in the southeastern edge or back core of the cloud. Along with REFL08, these are clear examples of clusters that are located in regions of very high extinction, resulting in stellar surface densities comparable to or lower than the field if a color selection is not applied. However, these clusters contain a large number of heavily reddened sources—easily distinguishable in \(JHK\) color composite images—and a significant number of NIRX sources that let them stand unequivocally as embedded clusters.

3. The third new cluster, NGC 2237, is located to the east of NGC 2244, in the region of the cloud historically identified as NGC 2237. The existence of this cluster was also suggested by Li & Smith (2005) in their study of 2MASS data.

4. The fourth cluster, REFL10, is much less prominent. It is located north of NGC 2244, and despite its low NIRX surface density compared to other star-forming regions in the complex, its 13 NIRX sources make it qualify as a cluster. REFL10 is an example of cluster that would not be significant if the NN distribution of NIRX sources was analyzed with a large value of \(j\), or if a color selection was not applied.

4. RESULTS

4.1. Identification of Clusters

In Figure 7 we show the location of NIRX stars with surface densities higher than the background level at 0.2 stars arcmin\(^{-2}\). All of the known clusters are traced well by these sources, which confirms that they are among the main regions of star formation in the Rosette complex. In this plot we also show the contours of

![Graph of NN distributions for bright NIRX stars. The top panel shows the distribution of 10th NN distances. The bottom panel is the distribution of 10th NN densities. In the top panel the solid line indicates the limit of distances shorter than 1.0 pc, while the dashed line indicates the midpoint value at 1.83 pc. In the bottom panel the equivalent limits in density space are also indicated.](image)

For the control fields we found 19 sources that had NIRX colors down to a maximum brightness of \(K = 15.75\). The mean 10th NN surface density of the 19 sources together is 0.18 stars arcmin\(^{-2}\) (0.82 stars pc\(^{-2}\)), which compares well with the mean value 0.2 stars arcmin\(^{-2}\) for the \(\mu_{10}\) distribution in the cloud survey areas. Thus, we considered a round value of 0.2 stars arcmin\(^{-2}\) as a background level for the NIRX population, below which we cannot assert that an embedded NIRX source has a density high enough to be distinguished from a field source with similar colors.

The minimum value of the \(D_{10}\) distribution in the survey is 0.311\(^{1}\), which represents a density of 29.5 stars arcmin\(^{-2}\) (136.3 stars pc\(^{-2}\)). This value is a good estimation of the typical local surface density in the central regions of RMC clusters. The midpoint between this minimum distance and the mean is 2.387 (1.1 pc), which corresponds approximately to \(\mu_{10} = 0.6\) stars arcmin\(^{-2}\) (2.77 stars pc\(^{-2}\)). It turns out that this value is a good estimate of the average embedded cluster size in the RMC.

4.2. Properties of Clusters

Once the clusters were identified, we proceeded to investigate their basic properties and how they are related in the context of the evolution of the star-forming complex. For each cluster we determined sizes, centers, number of members, and infrared excess fractions. These cluster properties were determined individually, isolating regions centered at each cluster density peak. The area of these individual cluster analysis regions varied from 25 to 120 arcmin\(^2\), depending on the apparent extension of the cluster. This way we were able to observe in detail structures occupying areas between 6 and 60 arcmin\(^2\).

4.2.1. Determination of Cluster Properties

Cluster boundaries are defined by the 0.2 stars arcmin\(^{-2}\) contour level in our NIRX NN density plots. All sources with \(K < 17.25\) mag within this contour level are considered potential cluster...
members. Cluster sizes are determined by measuring the area, $A_p$, within the cluster boundary and calculating the equivalent radius, $R_{eq} = (A_p/\pi)^{1/2}$.

The density peak, $X_d$, and the core radius, $R_{core}$, of each cluster were calculated with the formulation of CH85. The density peak defines the natural center of a cluster, and is simply the density-weighted average of the star positions in a given region:

$$X_d = \frac{\sum_i X(i) \mu_j(i)}{\sum_j \mu_j(i)}.$$  \hspace{1cm} (2)

Similarly, the core radius, $R_{core}$, is defined as the density-weighted average of the distance of each star to $X_d$:

$$R_{core} = \frac{\sum_i |X(i) - X_d| \mu_j(i)}{\sum_i \mu_j(i)}.$$  \hspace{1cm} (3)

In Table 1 we present the center coordinates (density peaks), core radii, equivalent radii, and average extinction values for each cluster. The latter were calculated from the $H - K$ colors. We also list the number of NIRX sources to $K < 15.75$ mag and the corresponding excess fraction. The excess fraction was calculated by comparing the number of infrared excess sources to the number of cluster members. The number of cluster members was determined by subtracting the expected number of background field stars from the number of stars having $K < 15.75$ within the cluster boundary. The number of field stars was determined for each cluster by scaling our off fields to the cluster areas and applying appropriate extinction corrections.

In Figures 9–20 we show images of each of these cluster regions, as well as the color-magnitude diagrams, color-color diagrams, and stellar radial profiles for all stars within the cluster boundaries. In the images, we marked NIRX sources brighter than or equal to $K = 15.75$ mag with crosses. In the $K$ versus $H - K$ color-magnitude diagrams we plot, for each cluster, all of the stars inside the corresponding 0.2 stars arcmin$^{-2}$ contour, and we marked with crosses those objects with infrared excess. We also plot the ZAMS locus and a pre-main-sequence evolution.
Fig. 8.—Final identification of clusters in the Rosette complex. The color scale contours indicate levels of surface density from the 10th NN analysis. The contours were constructed using a Nyquist box sampling of $1.5'$. Dotted line contours and thin solid line same as in Fig. 7.

| Cluster ID | R.A. (J2000) | Decl. (J2000) | $R_{\text{core}}$ (pc) | $R_{\text{equiv}}$ (pc) | $N_{\text{NIRX}} \pm (N_{\text{NIRX}})^{1/2}$ (K $< 15.75$) | NIRX (K $< 15.75$) | $\langle A_B \rangle$ (mag) |
|------------|--------------|---------------|------------------------|------------------------|---------------------------------------------------------------|---------------------|--------------------------|
| PL01       | 97.96        | 4.32          | 0.37                   | 1.16                   | 29 $\pm$ 5                                                   | 0.28 $\pm$ 0.05     | 8.1 $\pm$ 3.3             |
| PL02       | 98.31        | 4.59          | 0.94                   | 1.46                   | 32 $\pm$ 6                                                   | 0.33 $\pm$ 0.06     | 5.1 $\pm$ 2.8             |
| PL03       | 98.38        | 4.00          | 0.32                   | 1.69                   | 80 $\pm$ 9                                                   | 0.44 $\pm$ 0.05     | 6.8 $\pm$ 3.2             |
| PL04       | 98.53        | 4.42          | 1.10                   | 1.85                   | 89 $\pm$ 9                                                   | 0.24 $\pm$ 0.03     | 9.7 $\pm$ 5.2             |
| PL05       | 98.63        | 4.32          | 0.86                   | 1.31                   | 57 $\pm$ 8                                                   | 0.18 $\pm$ 0.03     | 7.2 $\pm$ 3.0             |
| PL06       | 98.66        | 4.21          | 0.73                   | 0.75                   | 13 $\pm$ 4                                                   | 0.52 $\pm$ 0.16     | 10.4 $\pm$ 4.0            |
| PL07       | 98.88        | 3.98          | 0.38                   | 0.88                   | 22 $\pm$ 5                                                   | 0.61 $\pm$ 0.14     | 8.9 $\pm$ 3.2             |
| REFL08     | 98.56        | 4.32          | 0.99                   | 1.30                   | 49 $\pm$ 7                                                   | 0.33 $\pm$ 0.05     | 11.8 $\pm$ 4.8            |
| REFL09     | 98.78        | 3.69          | 0.74                   | 1.49                   | 65 $\pm$ 8                                                   | 0.76 $\pm$ 0.09     | 9.8 $\pm$ 5.5             |
| REFL10     | 97.78        | 5.27          | 1.19                   | 1.15                   | 15 $\pm$ 4                                                   | 0.32 $\pm$ 0.09     | 3.2 $\pm$ 2.1             |
| NGC 2237   | 97.59        | 4.93          | 1.94                   | 1.91                   | 36 $\pm$ 6                                                   | 0.15 $\pm$ 0.03     | 3.1 $\pm$ 1.7             |
| NGC 2244   | 97.95        | 4.94          | 1.56                   | 2.30                   | 62 $\pm$ 8                                                   | 0.12 $\pm$ 0.02     | 1.4 $\pm$ 0.7             |

- $a$ Number of NIRX stars with 10th NN densities above 0.2 stars arcmin$^{-2}$.
- $b$ NIRX fraction with respect to total number of stars with $K < 15.75$ inside 0.2 stars arcmin$^{-2}$ contour.
- $c$ Average extinction toward cluster line of sight (estimated from background source colors).
Fig. 9.—Top left: K-band image (white symbols indicate locations of NIRX sources). Top right: Control magnitude diagram. Bottom left: Color-color diagram. Bottom right: Radial density profile for the area corresponding to cluster PL01. See text for explanation.
Fig. 10.—Same as Fig. 9, but for cluster PL02.
Fig. 11.—Same as Fig. 9, but for cluster PL03.
Fig. 12.—Same as Fig. 9, but for cluster PL04.
Fig. 13.—Same as Fig. 9, but for cluster PL05.
Fig. 14.—Same as Fig. 9, but for cluster PL06.
Fig. 15.—Same as Fig. 9, but for cluster PL07.
Fig. 16.—Same as Fig. 9, but for cluster REFL08.
Fig. 17.—Same as Fig. 9, but for cluster REFIL09.
Fig. 18.—Same as Fig. 9, but for cluster REFL10.
Fig. 19.—Same as Fig. 9, but for cluster NGC 2237.
isochrone of 1 Myr, both shifted to the distance of the Rosette. The indicated extinction vectors correspond to 3 times the mean value \( A_V \) in the cluster analysis box. Stars falling to the right of the 1 Myr isochrone are clearly affected by extinction toward the line of sight of the cluster, revealing their highly embedded nature. In the \( J - H \) versus \( H - K \) color-color diagrams, the same stars are located above the dwarf and giant star sequences along the reddening bands, with the NIRX sources located to the right of the ZAMS reddening strip. Those objects located at or near the zero-age sequences are most probably foreground stars or evolved cloud members.

The radial density profiles in the fourth panels of each cluster figure were constructed using annuli of decreasing width, each enclosing the same area (see, e.g., Muench et al. 2003) and centered on the weighted density peaks defined above. For these radial profiles we took into account all stars down to \( K = 17.25 \) inside the analysis boxes. In the plots we indicate the equivalent and core radii defined above. Clusters PL02, PL06, and REFL10 have the lowest surface densities and their profiles are poorly defined, but the rest present well-defined radial profiles, which show well-extended tails. In four cases—clusters PL01, PL04, PL07, and REFL09—the profiles show secondary peaks suggestive of structure. In the case of the nebula clusters NGC 2244 and NGC 2237, their radial distribution profiles decline slowly, which suggests a diluted core peak and a rather extended structure.

### 4.2.2. Comparison of Cluster Properties

Under the assumption that the NIRX sources trace well the extent of the clusters, the core and equivalent radii are good estimations of the total sizes of the clusters. The core radii, \( R_{\text{core}} \), of the Rosette clusters have a range of \( 0.69^\prime - 4.17^\prime \) (0.32–19.39 pc), with an average of \( 2.0^\prime \pm 1.0^\prime \) (0.93 ± 0.47 pc). Their equivalent radii, \( R_{\text{eq}} \), vary from \( 1.6^\prime \) to \( 4.9^\prime \) (0.74–2.28 pc), with an average of \( 3.1^\prime \pm 1.0^\prime \) (1.44 ± 0.47 pc). The distributions of these size estimates are shown in the top panel of Figure 21.

In the bottom panel of Figure 21 we show the distribution of the ratio \( \tau = R_{\text{core}}/R_{\text{eq}} \), which has a nominal peak at \( \tau = 0.7 \). In the study of FL08, where NN analysis was applied to a large sample of known cluster fields, they found that embedded clusters separated into two groups by their value of \( \tau \): those with ratios below 0.5 are denominated as centrally condensed (C-type clusters), while those with values closer to 1.0 are denominated as having a flat profile (F-type clusters). We found that only two of the RMC clusters, PL01 and PL03, have C-type ratios, and for three of the
clusters; PL06, REFL10, and NGC 2237, cores could not be easily determined and, for purposes of comparison, were given a ratio of $\tau = 1.0$.

The distribution of $\tau$ ratios is rather different from the one observed by FL08 in their larger and more heterogeneous sample of clusters: they found a larger fraction of compact, embedded clusters (44% of the sample) with well-defined cores, while in our sample, centrally condensed clusters appear to be scarce. However, we note that the NN analysis of FL08 was not applied on color-selected samples, but on all sources detected in a given field. From the observed distribution of cluster sizes and core-to-total size ratios it appears that the Rosette clusters have preferentially extended profiles.

As listed in Table 1, the observed NIRX fractions of the nebula clusters NGC 2244 and NGC 2237 are 12% ± 3% and 15% ± 2%, respectively, and therefore they are significantly smaller than those of the embedded clusters, which vary from 18% ± 3% in cluster PL05 to 76% ± 9% in cluster REFL09. Also, the average NIRX fraction in the molecular cloud areas is 41% ± 6%, i.e., almost 3 times as large as in NGC 2244 and NGC 2237. Curiously, the fraction observed for REFL10, which is also located at the nebula, is much closer to the average of the embedded clusters and actually slightly larger than those of clusters PL01, PL04, and PL05.

In Figure 22 we show the relation between the NIRX fraction, the median extinction value, and the equivalent radii of clusters. Extinction and cluster size are negatively correlated with a Pearson coefficient $\eta = -0.55$, while extinction and NIRX fraction (NIRXF) are positively correlated with a Pearson coefficient $\eta = 0.57$. Consequently, as shown in Figure 23, cluster equivalent sizes and core sizes are both negatively correlated with NIRXF, with Pearson coefficients $\eta = -0.61$ and $-0.54$, respectively.

We also found that the ratio $\tau$ was negatively correlated with NIRXF for clusters with a distinguishable core; this correlation is weaker ($\eta = -0.48$), but is similar to the relation found by FL08 for a sample of nearby clusters. The significance of these correlations in the context of the structure of evolution of the RMC clusters is discussed in § 5.

### 4.3. The Fraction of Stars in Clusters

Since NIRX sources trace the youngest population of stars within a star-forming region, we used the distribution of NIRX sources to investigate the fraction of stars located and forming in clusters. The fraction of NIRX sources in clusters was calculated by simply counting the number of NIRX sources within the cluster boundaries and comparing this value with the number of NIRX sources outside the cluster boundaries, correcting both for background contamination. We first considered the entire area of our survey, which provided us with an estimate of the number of stars that are currently located within clusters across the entire complex. Since the most recent episodes of star formation should be associated with the molecular gas, we next considered only the area within the molecular cloud, which provided us with an estimate of the fraction of stars currently forming in clusters.

For the first determination, we calculated that the total area covered by the FLAMINGOS survey is 7308 arcmin$^2$ (1579 pc$^2$), while the 11 clusters identified with our analysis occupy a total surface of 390 arcmin$^2$ (84 pc$^2$), i.e., 5.3% of the total survey area. The total number of NIRX sources detected is 1169 ± 34, out of which 549 ± 23 are located within the boundaries of the clusters, and 620 ± 25 are outside the boundaries. In order to correct for the background contamination, we scaled the number of NIRX sources observed in the control fields by a factor equal to the area of the molecular cloud minus the areas of the clusters and then divided by the area of the control fields. This expected number of NIRX sources due to background contamination was estimated to be 261 ± 17. The background correction for individual clusters is always smaller than the Poisson uncertainties, but it was also applied. Using these corrections, the number of NIRX sources

![Fig. 21.—From top to bottom: Distribution of core radii, equivalent radii, and core to equivalent radii ratios for the Rosette clusters.](image-url)
outside of clusters was 359 ± 19, and inside clusters was 531 ± 23. Therefore, the fraction of NIRX sources located in young clusters across the Rosette complex is 60% ± 5%.

The area of the molecular cloud was defined by the 0.8 K km s\(^{-1}\) integrated intensity contours of \(^{13}\)CO emission (Heyer et al. 2006), corresponding to \(A_V = 3.5 \pm 0.6\) mag using a recently derived conversion ratio (Pineda et al. 2007). This area equals 2684 arcmin\(^2\) (580 pc\(^2\)). The nine clusters located in the cloud occupy a total of 242 arcmin\(^2\) (52.3 pc\(^2\)) or about 9% of the RMC. The total number of NIRX sources detected in the molecular cloud is 589 ± 24, out of which 436 ± 21 are located within the cluster boundaries and 153 ± 12 are outside the boundaries. After correcting for field contamination, the number of NIRX sources located inside clusters is 429 ± 21 and outside clusters is 73 ± 8. Therefore, the fraction of NIRX sources currently forming in embedded clusters in the RMC is 86% ± 4%.

Interestingly, a total of 208 ± 15 NIRX sources are contained in clusters PL04, PL05, PL06, and REFL08, all located at the central core of the cloud. This corresponds to 48% ± 3% of the total number of embedded sources. Therefore, approximately half of the recent births in the RMC have occurred at the most dense region of the cloud.

4.4. Distribution of Sources with Respect to the Rosette Nebula

We analyzed the spatial distribution of those NIRX sources with 10th NN densities higher than the mean as a function of the distance to the center of NGC 2244. To do this, we determined...
the surface density of sources within concentric rings centered on NGC 2244 having a width of 1.0 pc. For the first 11 pc we were able to use complete rings, but farther away, we had to limit the angular extent of the rings to conform with the irregular shape of the survey boundaries. The surface density of sources in each ring or segment was calculated by dividing the number of sources in each segment by its area and then dividing by the surface density inside the first parsec circle.

This normalized radial NIRX source density distribution is shown in Figure 24 (top). In the plot we indicated the approximate locations of clusters described in this paper, as well as the main “regions” of the complex, defined by Blitz & Thaddeus (1980). Bottom: Averaged NIRX fractions in each of the cluster groups defined from the top plot appear to increase with distance from the Rosette Nebula.

In the bottom panel of the figure, we indicate the average fraction of NIRX sources in clusters as a function of distance, averaged in five groups of clusters that are roughly traced by the distribution shown in the top panel. The cluster groups used are as follows: the first group includes NGC 2244, NGC 2237, and REFL10; the second group includes PL01 and PL02; the third group includes PL04, PL05, and REFL08; the fourth group includes PL03 and PL06; and finally, the fifth group includes clusters PL07 and REFL09.

4.5. Low-Density Population

In order to investigate the low-density star-forming component in the cloud, we closely examined the region between the central core and the back core. This region corresponds to field 09 of our survey. This field was chosen because the seeing and observing conditions for it were particularly good. Specifically, the average scatter of colors down to \( K = 17.25 \) remains below 0.109 mag (similar to the average for bright-end bins) across the whole field (see Fig. 25). This superior quality was achieved because the southeastern quadrant of the field, which in other fields presents high stellar profile distortions, overlaps with the good quality northwestern quadrant of field G1. Selective averaging of photometry in these overlapping quadrants permitted the reduction of the total color scatter.

No clusters were found in this field, but a small group of NIRX sources coincide well with a roughly filamentary core in the cloud located southwest of the PL06 cluster region (see Fig. 7). Our NNM analysis does not produce a new cluster identification for this core, but we counted the number of NIRX sources in the whole field down to brightness limits of 15.75, 16.25, 16.75, and 17.25 mag. We counted the number of NIRX sources in the control fields at these same magnitude limits. In order to make a conservative estimate, we limited the counts to a circular area with a radius of 1500 pixels centered on pixel position [3000, 2400]. This delimits the area of best photometric quality after the polynomial correction, as described in § 2.

We compared these NIRX counts in field 09 with the expected number of field NIRX sources at these same limits in an equivalent area of high photometric confidence in the control fields, adding again, a mean extinction level of 5.0 mag to account for stars that would have excess colors after reddening. A second comparison was done by averaging the number of observed NIRX sources in equivalent photometric confidence circular areas of survey fields 03, 13, 14, and 15. These fields are located in regions of the complex where the CO emission from the molecular cloud is lower than average, and thus they can help to determine if the NIRX sources of field 09 could indeed be a local enhancement near the core of the RMC.
16.75, and 17.25, respectively. The counts are also higher than those located outside the main CO emission regions of the molecular cloud was very small; the majority of them were in fact located in areas mostly devoid of strong molecular hydrogen emission. The shaded histogram indicates the scaled number of “expected” background NIRX sources, averaged from counts in the control fields (also in the best PSF circular areas), and adding a uniform extinction value of 5.0 mag.

In Figure 26 we compare the counts described above in the form of cumulative histograms: apparently, field 09 surpasses significantly the expected number of NIRX sources from the control field and the off-cloud areas, with counts 4.8, 5.6, 3.5, and 2.2 times larger than those in the control field at \(K < 15.75, 16.25, 16.75, \) and 17.25, respectively. The counts are also higher than the averaged counts of survey fields 3, 13, 14, and 15 by factors of 1.3, 1.5, 1.6, and 1.8, respectively. This suggests that the region of the cloud observed in field 09 could have a significant number of young source candidates not associated with clusters. Furthermore, \(JHK\) color images of selected regions of the field show a number of highly reddened sources. Some of these sources have thin nebulosities, and coincide with or are located close to stars with near-infrared excess emission. These sources are not included in our infrared excess catalog because they were not detected in our \(J\)-band observations, and therefore we do not have three colors to determine if they exhibit excess emission.

In addition, we counted the number of sources with no \(J\)-band photometry and \(H - K > 1.5\) mag at the same \(K\) brightness limits mentioned above. It is not possible to assure that these sources belong to the cloud, especially for \(K > 15.75\), where the scatter increases and the contamination by background galaxies worsens. However, we noticed that the number of these sources that are located outside the main CO emission regions of the molecular cloud was very small; the majority of them were in fact located within the cluster areas (see Fig. 27). Therefore, these red sources could be tracing the location of young sources too. Also, no stars with \(H - K\) colors this large were found in the control field. In Figure 27 we show the distribution of the sources with \(H - K > 1.5\) in the survey areas down to \(K < 17.25\) mag, respectively. In Table 2 we show the number counts of \(H - K > 1.5\) sources, separating those located outside the 20.0 K km s\(^{-1}\) CO contours (\(A_V \approx 3.5\) mag), and then dividing the ones located inside the contours into those within and outside the cluster areas. After correcting by background (in this case by subtracting the scaled number of in-survey/off-cloud sources) we estimate that the average fraction of objects with \(H - K > 1.5\) located inside the molecular cloud projected area but outside the clusters is approximately 21% ± 4%. The fraction is slightly larger than the one obtained from counts of NIRX sources (14% ± 4%), possibly due to the fact that our red source counts are less restricted, as we cannot limit their range in \(J - H\). Counts of sources with large \(H - K\) values have been used before to identify highly embedded clusters with good results (e.g., Homeier & Alves 2005; Ojha et al. 2004); in our case, our maps show that large \(H - K\) color sources trace well the regions we identified as clusters, but also show a population at the 10%–20% level that might be distributed along the rest of the cloud.

5. DISCUSSION

5.1. Clusters as a Dominant Mode of Formation

Observations of nearby molecular clouds such as Orion, Perseus, and Monoceros suggest that most stars in these clouds form in embedded clusters (LA91; CA00). In the RMC, approximately 86% of the present-day star formation occurs in embedded clusters, in excellent agreement with the previous results for nearby clouds. This indicates that cluster formation is also the dominant mode of star formation in clouds beyond 1 kpc. Cluster formation appears to be well distributed across the Rosette complex, but the clusters themselves are confined to a rather small fraction (5%) of the total area of the cloud. Comparison of the distribution of embedded clusters with the distribution of molecular gas (WBS95) reveals that the embedded clusters are associated with the most massive molecular clumps in the cloud, which are also the most dynamically evolved. This is similar to what was found in the Orion B cloud (Lada 1992).

While the most massive clumps in the Rosette are responsible for the production of the embedded clusters, some of less massive clumps could be associated with the distributed population. The number of sources exhibiting near-infrared excess in field 09 and the number of sources with \(H - K > 1.5\) across the cloud could indicate that a distributed population of young stars formed in addition to the cluster population. However, the formation of...
this distributed population could account for no more than 20% of the total star formation within the RMC. Characterizing the distributed population is difficult due to several observational constraints. For example, the large photometric scatter of faint sources along with the field star contamination restrict our study to the brighter (likely higher mass) sources, which are expected to be less numerous than the fainter (likely lower mass) ones. Spectroscopic observations and mid-infrared imaging would help to establish the number of highly reddened sources outside the cluster regions. Also, the nature of the distributed population in molecular clouds is somewhat unclear, as discussed by CA00, precisely because these sources permeate through large areas of the molecular cloud in and between regions of cluster formation and thus do not have a clear origin. Such a population could be the residual of a slightly older generation of star formation, a subproduct of cluster formation resulting from mass segregation or ejection, or belong to a population located in the foreground or background of the cloud.

5.2. Rapidly Evolving Clusters

The mortality rate of embedded clusters in the Milky Way is quite high. Less than 10% of clusters survive their emergence from molecular clouds and live longer than 10 Myr, and less than 4%–7% survive to become bound clusters the age of the Pleiades (LL03). This early disruption is most likely linked to low star formation efficiency and the rapid destruction of the molecular clouds. Similar results are found in other galaxies (e.g., Fall et al. 2005).

The observed distribution and properties of the embedded clusters in the Rosette complex may be revealing some of the first signs of such early cluster evolution. The clusters in the Rosette appear to be, on average, slightly larger than those located in other clouds: the cluster equivalent radii range from ~0.75 to 2.3 pc, with a mean of 1.44 and a median of 1.46 pc. The largest cluster in the complex is NGC 2244, with an equivalent radius of 2.3 pc. For comparison, the sizes of clusters listed in the catalog of LL03 range from ~0.3 to 3.8 pc, but have a mean of 0.8 pc and a median of 0.62 pc. Only a few clusters in this catalog, such as MonR2, Gem4, NGC 2282, and Trapezium/ONC, have radii larger than 1.5 pc.

It is unlikely that the Rosette is systematically forming larger than average clusters. Instead, the large cluster sizes may be due to dynamical evolution of the cloud leading to the beginning of cluster expansion and eventual dispersal. Indeed, our data suggest that cluster sizes in the Rosette may be related to cluster evolution in several ways. First, we found a negative correlation between extinction and cluster sizes (Fig. 22), indicating that the most extended clusters are the least embedded and are the ones that are emerging from the parental molecular material. Cluster sizes are also inversely proportional to their infrared excess fraction (Fig. 23). It has been shown that the infrared excess fraction in young clusters is initially high and decreases rapidly as a function of cluster age such that clusters with ages >5 Myr have no or extremely small excess fractions (Haisch et al. 2001). In the Rosette, excess fraction decreases with increasing cluster size, implying that clusters expand relatively quickly (in a timescale comparable to the T Tauri phase). Furthermore, analysis of the density structure of the embedded clusters may also indicate the beginnings of cluster evolution. For example, even though some of the Rosette clusters exhibit a well-defined core from our NN analysis, others appear to be extended well beyond this core. Indeed, the ratio of the core size to the total size, $\tau$, is 0.5 or above for six out of eight young clusters with defined cores (Fig. 21), indicating that most of the Rosette clusters do not have prominent central condensations. In addition, $\tau$ decreases with increasing infrared excess fraction (see Fig. 23). A similar correlation was found by FL08 in their analysis of local clusters. In the Rosette, clusters with $\tau \geq 0.5$ have an average infrared excess fraction of 27%, whereas clusters with $\tau < 0.5$ have an average IRX fraction of 52%. These results suggest that clusters form as compact units and later become less centrally condensed. This initial expansion appears to start quickly after formation and likely develops within a few megayears, favoring a scenario of rapid disruption and cluster dispersal.

5.3. Influence of the H II Region and Sequential Star Formation

The layout of the Rosette complex led WBS95 and PL97 to suggest that the formation of the clusters was triggered by the expansion of the nebula into the cloud, resembling the picture of sequential star formation proposed by Elmegreen & Lada (1977). In this model, the shock front from an expanding H II region would trigger the formation of a new OB association in an adjacent molecular cloud, which would later trigger a third group, and so on. We can use the distribution of young stars and clusters in our survey to investigate what effect the H II region has had on the star-forming properties of the cloud.

Star formation in the Rosette appears to be concentrated into four main areas of the complex, as illustrated in Figure 24. The most prominent is the Rosette Nebula itself, which contains the clusters NGC 2244, NGC 2237, and REFL10. The next concentration of star formation is located between 10 and 20 pc from the center of NGC 2244, corresponding to the RMC ridge. This region is located closest to and overlaps with the ionization front of the H II region and contains clusters PL01 and PL02. It has the lowest levels of star-forming activity. Star formation may be inhibited in this area due to the effects of the ionizing radiation. Hot ionized gas might accelerate the evaporation of gaseous material surrounding a forming cluster, resulting in the end of the star-forming process.

The third concentration of young stars is located 20–30 pc from NGC 2244 and contains clusters PL04, PL05, REFL08, and PL06 at the RMC central core, and PL03, located in a gas clump (core D).
outside the main area of the cloud. The four clusters in the central core account for 48% of the present-day star formation in the molecular cloud while only covering roughly 4% of the cloud area. These cores are associated with four of the most massive cores in the cloud (WBS95). Similarly high concentrations of star formation have been observed in other molecular clouds such as Orion, W3/W4/W5, and Perseus, where approximately half of the young stars are found in only one to a few embedded clusters (LA91; Carpenter et al. 2000; Jørgensen et al. 2006). The RMC central core appears to coincide with the edge of the Rosette Nebula, as shown by images of radio continuum and 25 μm IRAS emission. The studies of Celnik (1985), Cox et al. (1990), WBS95, and Heyer et al. (2006) agree that the nebula and molecular cloud have their most intense interaction at this region, and this may indicate the recent passage of the shock front from the nebula. The interaction with the shock front may have triggered or stimulated the production of stars here, resulting in the second most active region of star formation in the complex.

The last concentration of star-forming activity is at the back core of the cloud. This region contains clusters PL07 and REFLO9. These two clusters appear to have formed in a region of the cloud located beyond the main interaction with the nebula (Heyer et al. 2006). Given their distance from the shock front, it is unlikely that the formation of these clusters was triggered. This reinforces the suggestion by PL97 that star formation in this part of the cloud occurred spontaneously.

Surprisingly, we do find the first evidence for a possible temporal sequence in star-forming events in the Rosette. The average cluster infrared excess fraction increases as a function of distance from NGC 2244, suggesting that the embedded clusters are progressively younger the farther they are from the nebula. The existence of this apparent age sequence indicates that star formation in the Rosette did indeed take place sequentially in time, but not in the way proposed by Elmegreen & Lada (1977). Instead, it appears that the overall age sequence of cluster formation is independent of any interaction with the expanding H II region, but rather may be primordial, possibly resulting from the formation and evolution of the molecular cloud itself. While the existence of the H II region cannot be responsible for the sequence of cluster ages, it does appear to have a significant impact on the underlying sequence by either enhancing or inhibiting the star-forming process.

5.4. Summary

1. In this paper we present the results of a deep near-infrared survey of the Rosette complex. The survey was made with the wide-field imager FLAMINGOS at the Kitt Peak 2.1 m telescope and covers all the main areas of the Rosette Nebula and the Rosette Molecular Cloud.

2. We analyze the distribution of young stellar sources in the complex by estimating the surface densities of objects with infrared excess, using a variation of the nearest neighbor method, which allows us to find clusters with minimum populations of ~30 members.

3. We confirmed the existence of the seven embedded clusters found by visual inspection by PL97 and found four more clusters in the complex. Two of these clusters are deeply embedded in the molecular cloud, and the other two are located west of NGC 2244 in the Rosette Nebula.

4. The young cluster population accounts for 60% of the stars in the complex, and approximately 86% of the youngest stars, located in the molecular cloud. This implies that the majority of stars in the Rosette form in embedded clusters, similar to nearby clouds.

5. The sizes of clusters in the Rosette complex appear to be anticorrelated with their mean extinctions and infrared excess fractions, which suggests that clusters form as compact units then expand shortly after formation. The timescale for this process is similar to or even shorter than the T Tauri phase, as evidenced by the significant NIRX fractions and deeply embedded status.

6. The distribution of young clusters suggests a division of star formation into four main regions coincident with the largest features of the cloud: the first is the Rosette Nebula, which contains the oldest clusters; the second is the ridge, located near to the ionization front of the H II region; the third is the central core of the molecular cloud, where the main interaction between the nebula and the cloud is located, and approximately 50% of the young stellar population was produced. The fourth region of formation is at the back core of the cloud, located farthest from the nebula.

7. The averaged infrared excess fraction of these regions appears to increase as a function of distance from the Rosette Nebula, which is suggestive of a sequence of cluster ages across the cloud. Rather than being triggered by the H II region, this sequence appears to be primordial, possibly resulting from the formation and evolution of the molecular cloud. The H II region appears to enhance or inhibit the underlying pattern of star formation in the cloud.

We want to thank an anonymous referee, whose revision improved the content and quality of our manuscript. We also thank Charles J. Lada for useful discussion of this study. We acknowledge Andrea Stolte for developing the codes that permit the zero-point correction described in § 2. We thank Jonathan Williams for additional discussion.

This project would not have been possible without the effort of all members of the FLAMINGOS team. We thank Ron Probst and all the Kitt Peak National Observatory staff for their kind assistance. We appreciate the tireless dedication of Nick Raines in every step of the FLAMINGOS project. We are grateful to the instrument team at the University of Florida, including Kevin Hanna, Jeff Julian, and David Hon. We also appreciate the hard work of UF students and postdoctoral researchers Joanna Levine, Kelly McFarland, Eric McKenzie, Noah Rashkind, Chris Foltz, Matthew Horrobin, Katherine Wu, Andrea Stolte, and Aaron Steinhauer.

Carlos Román-Zúñiga wants to acknowledge CONACYT, Mexico for a fellowship that sponsored his doctoral studies at the University of Florida.

FLAMINGOS was designed and constructed by the IR instrumentation group (PI: E. A. Lada), which is supported by NSF grant AST 97-3367 and AST 02-02976 to the University of Florida.

The data presented in this work were collected under the NOAO Survey Program Towards a Complete Near-Infrared Spectroscopic Survey of Giant Molecular Clouds (PI: E. A. Lada), which is supported by NSF grants AST 97-3367 and AST 02-02976 to the University of Florida.

This research was also supported in part by the National Aeronautics and Space Administration under grant NNG 05D66G issued through the LTSA program to the University of Florida.

The FLAMINGOS near-infrared survey of giant molecular clouds could not be possible without the support from the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA), under cooperative agreement with the National Science Foundation.
This publication makes use of data products from the Two Micron All Sky Survey (2MASS), which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

**Facilities:** KPNO:2.1m (FLAMINGOS)

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