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THE YOUNG OPEN CLUSTERS NGC 2244 AND NGC 2264; REVISITED

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RESUMEN

Esta investigación analiza nuestro entendimiento de la región Norte de Monoceros. En especial, las regiones de los cúmulos abiertos NGC 2244 y NGC 2264 son estudiadas críticamente con objeto de determinar sus orígenes, evolución y similitudes.

Se presentan nuevos valores de los radios de los cúmulos, edades y masas totales. Se derivan velocidades radiales promedio de $+33.7 \pm 3.0$ km s^{-1} para NGC 2244 (incluyendo 9 estrellas) y de $+20.9 \pm 5.1$ km s^{-1} para NGC 2264 (9 estrellas). Se incluye un valor aproximado de la eficiencia de la formación estelar en la región, como asimismo se estima su cinemática y ubicación en los brazos de la Galaxia.

Considerando las distancias y efectos de rotación galácticos en la dirección de esta región, los cúmulos analizados se encuentran suficientemente distantes para negar toda posibilidad de interacción física. Además la composición estelar y orígenes parecen distintos. El mecanismo de colisiones de masas interestelares es favorecido como el proceso inicial en el caso de NGC 2244, en cambio el mecanismo de explosión de supernova y subsecuente fragmentación parecen haber jugado un importante rol en la formación de NGC 2264.

ABSTRACT

In this study our current phenomenological understanding of the Northern Monoceros region is reviewed. In particular, the largest young open clusters in the area, NGC 2244 and NGC 2264, are critically studied in order to determine their origins, evolution, and similarities.

We present new determinations of the cluster radii, ages, and total masses. Mean cluster radial velocities are derived as $+33.7 \pm 3.0$ km s^{-1} for NGC 2244 (including 9 stars) and $+20.9 \pm 5.1$ km s^{-1} for NGC 2264 (9 stars). A rough estimate of the star formation efficiencies in the region is also included, as well as a discussion of their kinematics and locations in the spiral arms of the Galaxy.

Based on their distances and considering the effects of galactic rotation in the direction of this region, the two clusters are separated widely enough to negate any possible physical interaction. Also their stellar population compositions and origins seem dissimilar. We favor a cloud-cloud collision as the initial triggering mechanism in the case of NGC 2244, whereas, supernova explosion and cloud fragmentation seem to have played an important role in the formation of NGC 2264.

Key words: **CLUSTERS-OPEN**

I. INTRODUCTION

The role of young open clusters ($t_{age} \leq 10^8$ yr) in the study of star formation processes is extremely important because they represent the first stage in the evolution of young stellar complexes. The variety of scenarios provided by open clusters, generally still embedded in dense gas and dust clouds, makes it difficult to generalize or reduce their star formation histories to simple mechanisms.

Regions such as Taurus-Auriga, Orion, Ophiuchus, Monoceros, etc. are abundant in molecular clouds, H II regions, dark nebulosities, young open clusters, and several indicators of recent star formation. In Northern Monoceros the stellar associations Mon OB1 and Mon OB2 are the largest

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stellar complexes. The open cluster NGC 2244 (C0629+049) is the youngest and most active stellar group in the Mon OB2 association, similarly NGC 2264 (C0638+099) represents the largest cluster in Mon OB1. These clusters are situated around bright nebulosities and apparently seem spatially related through the Monoceros Loop which is believed to be a supernova remnant (Davies 1963; Milne and Hill 1968; Gebel and Shore 1972) due to its non-thermal emission with a radio spectral index, $\alpha = -0.50$ ($F_\nu \sim \nu^\alpha$).

The cluster NGC 2244 according to Trumpler's classification is II 3 P, meaning detached of slight concentration, composed of bright and faint stars, and poorly populated ($\leq$ 50 stars). Likewise, the Trumpler class for NGC 2264 is IV 3 P, meaning not detached in addition to the descriptions for the previous cluster. Current estimates for cluster ages are 3×10^6 yr (Lyngå 1981), 4×10^6 yr (Ogura and Ishida 1981) for NGC 2244, and 2×10^7 yr (Lyngå 1981; Kalandadze, Kuznetso, and Voroshilov 1986), 5×10^6 yr (Sagar and Joshi 1983), and 10^7 (Sagar *et al.* 1986) for NGC 2264. These estimates place the region among the youngest in the Galaxy in terms of stellar ages.

This active stellar forming region is of great interest as a testing ground of many hypotheses concerning the origin and evolution of the singular young objects abundantly present here. A study of extinction and distances has been presented by Pérez, Thé and Westerlund (1987, Paper I hereafter). We have also estimated stellar parameters by mean of Strömgren data (Pérez *et al.* 1989, Paper II), spectral types for a large sample of stars in the field of NGC 2244 and NGC 2264 (Pérez *et al.* 1990a, Paper III), and studied the infrared emission of a considerable sample of stars in the cluster fields (Pérez *et al.* 1990b, Paper IV).

The main purpose of this paper is to review our understanding of the Monoceros region as well as the overall structure of the region. Although we have previously concentrated on the nature of the stellar population we will focus on general cluster characteristics in this study. We present new determinations of some cluster properties such as radii, ages, radial velocities, and total masses.

II. BRIEF CLUSTER HISTORIES

After Walker (1956) presented the H-R diagram of NGC 2264 showing an impressive number of low-mass stars above the main sequence, numerous theoretical studies tried to explain such unusual positions. Nevertheless, critical voices were raised concerning the membership of many of these assumed pre-main-sequence (PMS) objects (e.g., Underhill 1960; McNamara 1976 quoted by Warner, Strom and, Strom 1977). Similarly, for stars above the main-sequence in other known Walker's clusters, similar criticisms about their memberships were published (e.g., in NGC 6530 (M8) see Thé 1960 and Chini and Neckel 1981, among others). In the meantime, Vasilevskis, Sanders, and Balz (1965) published a critical study of membership based on proper motion calculations. A large number of the suspected PMS objects turned out to be field stars, generally located in the foreground since there is an optically thick cloud immediately behind this cluster. Out of his original sample of 239 stars, Walker (1956) ruled out 43 stars, or 18%, as being field objects from simple considerations of reddening and location in the cluster. Later Vasilevskis *et al.* (1965) from a sample of 245 stars, found that 105 or 43% have probabilities of membership, P, lower than 0.50, and 59 or only 24% have P $\geq$ 0.90. Recently, Zhao *et al.* (1985) reevaluated the probabilities of membership using Vasilevskis's *et al.* data and found that an even lower number of stars are probable members of the cluster. From the same sample of 245 stars, 135 or 55% were found with P < 0.50, and 11 or only 4.5% with P $\geq$ 0.90. Even for some of the stars believed to be probable members we have questioned in Paper III their memberships based on radial velocity considerations. In conclusion, quantitatively, the number of suspected PMS stars has decreased dramatically, leaving us with two main groups of objects with similar kinematics; massive evolved or main sequence stars (OB-type) and a very well-distinguished group of T Tauri stars. Among the first group of stars we concede that probably there are a few young objects such as the stars 62 (W90) and 72 (W100).

The younger cluster, NGC 2244, has raised considerably fewer disagreements over the years. This cluster is undoubtedly formed by very massive stars, formed in an episode of star formation subsequent to that in NGC 2264. In an early study of proper motions, van Schewick (1958) found 22 probable and 4 possible stellar members. Later, Johnson (1962) in a photometric study of 46 bright stars identified 34 probable cluster members. Likewise, Riddle (1972) from kinematical considerations found 10 stars to be possible members. In an extensive study of proper motions for 287 stars (complete down to V = 14.0 mag), Marschall, Van Altena, and Chiu (1982) assign probabilities of membership larger than 90 %, P $\geq$ 0.90, to only 34 stars (with high proper motion quality determinations) inside a circle of 25 arcmin of diameter centered on star No. 122. Recently, Guseva, Kolesnik, and Kravchuk (1985) considered 2100 stars of types O, B, and A in the cluster field and found that only 16 of the O-B2 stars were associated with the cluster. It is likely that other stars surrounding NGC 2244 are members of the Mon OB2 association of which this cluster is a part. It is rather remarkable that mostly bright early-type stars belong to NGC 2244. The cluster H-R diagram shows no observable objects above the ZAMS among its probable members, except for a few of its Hα emitters. It has, however, two stars which are already evolving away from the main sequence (stars No. 122, and 203). The five Hα emitters found in the region seem to have different kinematics and are in general of a later spectral type than most probable cluster-members.

III. CLUSTER MORPHOLOGY

a) *Dust, Nebulosity and Molecular Clouds in Northern Monoceros*

This galactic equatorial region is abundant in emission nebulosity, opaque clouds, dark globules, and young open clusters. Figure 1 presents a synopsis of the best known objects in the region.

More than 30 years ago, Morgan, Strömgren, and Johnson (1955) drew attention to the bright nebulosity extending between the Rosette Nebula (NGC 2237) and S Mon (NGC 2264). Later Morgan *et al.* (1965) in a more detailed study suggested that the clusters NGC 2244 and NGC 2264, and the Monoceros Loop (see Figure 1)

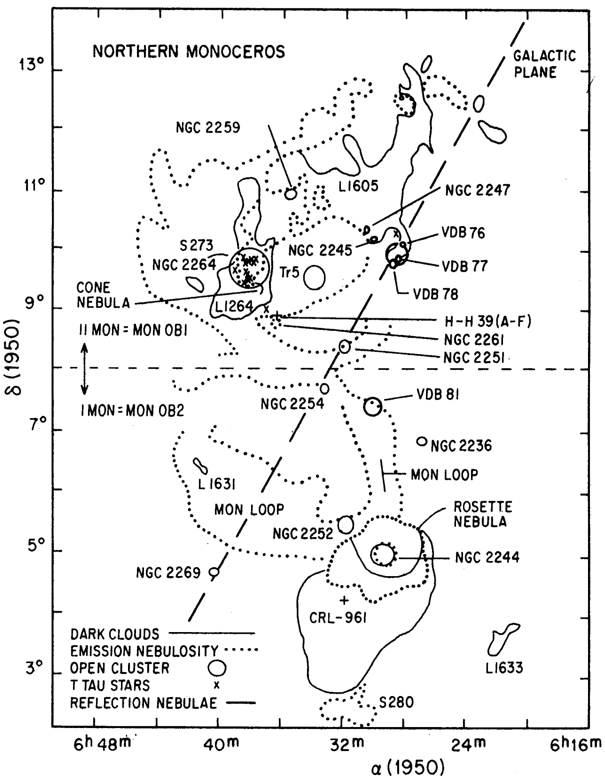

Fig. 1. Map of the Northern Monoceros region showing some of the most important optical objects. This map has been adopted from Blitz (1980). Some characteristics of these objects are listed in Table 1.

were spatially related due to two independent observations; similar cluster diameters, and similar distances of both clusters if the ratio of total to selective extinction, R, is assumed to be 6 (Johnson 1965) for NGC 2244.

The regions under study have been extensively observed at radio wavelengths and such observations will not be reviewed here; nevertheless, we will summarize some of the significant results in a qualitative manner. The major probe to detect molecular compounds has been the studies on carbon dioxide, ^{12}CO, mostly because it is the most abundant molecule with a microwave spectrum and due to its approximately constant abundance ratio to molecular hydrogen, H_2 (Thaddeus 1977). Additionally, Burton and Gordon (1978) have found that CO follows the same kinematics as the H I gas. We will list some of the features discovered through radio wavelength studies.

NGC 2244.

i) In the study of the distribution of the neutral hydrogen, through the profiles of the 21-cm line, Menon (1956) found three clouds represented by the radial velocity peaks at +10, +19, and +38 km s^{-1}. Later, Raimond (1966), in a more detailed study of H I, calculated the mass for the whole association, Mon OB2, as 1.5×10^5 $M_\odot$, and determined that the neutral cloud "c" was associated to the Rosette Nebula based on its radial velocity.

ii) Blitz and Thaddeus (1980) in a study of the CO structure in the Rosette Nebula found approximately 15 clumps with radial velocities, Vr_{LSR}, ranging from 10 to 21 km s^{-1}. According to the galactic rotation (equations (4), (5), and (6) in this paper) we derived distances of 880 pc and 1900 pc, indicating as was suggested by Guseva *et al.* (1985), that some of the CO emission comes from the foreground dust and gas cloud which is situated at nearly the distance of NGC 2244.

iii) The CO profiles are centered around the strong infrared source, CRL-961, (Cohen 1973), which is believed to be a protostar similar to the Becklin-Neugebauer object. Guseva *et al.* (1985) have suggested that this object is located at a distance of 800 pc lying in the foreground cloud. This cluster seems to be at the edge of such molecular complexes.

iv) Celnik (1983a, 1985), by studying the Hα emission line in the Rosette Nebula and the radio continuum, has found a clumpy structure which mimics the emission nebula. He also noticed that the observed flux density corresponds to the *UV* emission from the O stars of NGC 2244. Estimates of the mass in dust form and in the ionized cloud were presented as M_{dust} = 5.4×10^3 $M_\odot$ by Celnik

(1983b) and $M_{HII} = 2.30 \pm 0.1 \times 10^4$ $M_\odot$ by Celnik (1985).

v) It has been estimated that the central region of the Rosette Nebula, where NGC 2244 resides, consists of a shell of ionized material expanding at a velocity of about 20 km s^{-1} (Smith 1973; Fountain, Gary, and O'Dell 1979).

vi) The molecular complex detected through CO emission by Blitz and Thaddeus (1980) extended up to 100 pc and is apparently embedded in the H I cloud "c" having a similar mass of 1.3×10^5 $M_\odot$.

NGC 2264.

i) The large scale structure in this cluster is dominated by two stellar and cloud associations in expansion (Menon 1956; Viennot 1965). Studies of the distribution of the H I in the region by Menon (1956) and Raimond (1966) have indicated that it is arranged in several sparse clouds but the cluster is not centered in either of them. Around NGC 2264, Raimond found three neutral clouds, "b", "f", and "f′", being cloud "b" more closely associated with the cluster. He was unable to ascertain if the cluster was within the cloud. The dark cloud immediately behind the cluster is placed between these two cloud distribution peaks indicating the lower density of H I in this absorbing region probably due to the formation of H_2. The estimate of the H I mass for the entire Mon OB1 association is 1.8×10^4 $M_\odot$ (Raimond 1966).

ii) In this cluster the CO mapping for the ^{12}CO and ^{13}CO molecules has been extensively carried out by several authors (e.g., Crutcher, Hartkopf, and Giguere 1978; Blitz 1980; Sargeant *et al.* 1984, etc). The structure of the CO clouds appears to be highly fragmented. The mass of the molecular cloud associated with the cluster was estimated as 2×10^4 $M_\odot$ by Crutcher *et al.* (1978).

iii) The infrared source discovered by Allen (1972), IRS1, is not as intense as its counterpart in NGC 2244, CRL-961, however, it has some

TABLE 1

CLUSTERS AND STARS IN BETWEEN NGC 2264 AND NGC 2244
(North to South)

Object	α (1950)	δ	Open Cluster	$E(B-V)$	$(m-M_v)$	r (pc)	Name	Reference[a]
NGC 2259	6:35.8	10:55	Yes	....	12.96	3900		II2P(Trumpler)/ 7
NGC 2247	6:31.7	10:22	No	0.44	9.52	800		3
NGC 2245	6:31.3	10:11	Yes	0.25	9.77	900		3
NGC 2264	6:38.3	9:56	Yes	0.06	9.88	950	SMon Cluster	IV3P/Paper I
Trumpler 5	6:33.9	9:29	Yes	0.70	11.90	2400		2
NGC 2261[b]	6:36.4	8:46	No	var.	9.88	950	RMon, Hubble's Neb.	4
NGC 2251	6:32.0	8.24	Yes	0.12	11.00	1330		6
NGC 2254	6:33.3	7:43	Yes	0.45	11.69	2170		1
NGC 2236	6:27.0	6:52	Yes	0.51	12.68	3430		III2P/ 1
HD 47129[c]	6:34.7	6:11	No	0.37	11.10	1660	Plaskett's star	5
NGC 2246	6:31.1	5:08	No	....	....	....		
NGC 2252	6:32.3	5:25	Yes	....	11.01	1590		8
NGC 2237-39	6:28.3	4:59	No	var.	11.11	1670	Rosette Neb.	
NGC 2244	6:29.7	4:54	Yes	0.47	11.11	1670		II3P/Paper I
NGC 2269	6:41.3	4:37	Yes	0.44	10.79	1440		2
NGC 2262	6:35.8	1:14	Yes	....	13.38	4750		8
NGC 2232	6:24.1	−4:43	Yes	0.07	7.81	370		1
NGC 2215	6:18.6	−7:16	Yes	0.33	10.44	1225		1

a. References: 1) Becker and Fenkart 1971; 2) Lyngå 1981; 3) Witt and Schild 1986; 4) Cohen and Schwartz 1983 for NGC 2261 assumed same distance as NGC 2264; 5) Wallerstein and Jacobsen 1976; 6) Mermilliod 1981; 7) Bok 1949; 8. Collinder 1931 quoted in Alter *et al.* 1970.

b. RMon, Sp. Type: G5p, mag = 9.3v, Vr = +12 km s^{-1} Wilson 1963; vr = +15.5 km s^{-1} Abt 1970; RW Auriga star?

c. Sp. Type: O8e, mag = 6.05v, eclipsing binary, P = 14.3961 d, Vr = +24.5 km s^{-1} Wilson 1963; Vr = +24.32 km s^{-1} (from 105 meas.)

molecular condensation around it. The underlying source is believed to be an early B-type star (Schwartz *et al.* 1985).

iv) While NGC 2264 is a very weak radio source, more than a dozen molecular species have been identified in the neighborhood of this cluster such as, CS, HCN, OH, H_2CO, NH_3, etc., (see review by Walsh 1980). The picture that emerges from these observations is that the velocity structure is complex, splitting into three velocity components, 4.8, 9.2, and 10.7 km s^{-1} (Crutcher *et al.* 1978) at several positions. Most of the molecular absorption seems to originate from discrete sources or globules. The strong kinematic association of the molecular and the H I clouds has been confirmed.

v) The dense obscuring cloud behind the cluster pointed out by Herbig (1954), extends in the North-South direction and is of variable width. Many Hα emitters are embedded in it and it seems to be correlated with the H I and molecular clouds surrounding the cluster.

In other regions the physical interaction among molecular, neutral clouds and star clusters has been also well established. Recently, Liu *et al.* (1988) in a study of the stellar and molecular, CO, radial velocities for four young open clusters, found good correlations between the LSR velocities for three of them.

We have listed in Table 1 the most well-known clusters and possible related objects present in Northern Monoceros (from North to South). No gradient in distances nor in color excesses are found for these objects; however, it is possible to distinguish two groups or associations: Mon OB1 in the North and Mon OB2 to the South. The kinematic characteristics of R Mon (NGC 2261) and HD 47129 (Plaskett's star), indicate that they are related to NGC 2264 and NGC 2244, respectively.

b) *Determinations of Radii*

From photographic plates taken at the Brigham Young West Mountain Observatory with the 61-cm reflecting telescope of both clusters we estimated the cluster radii. The limiting magnitudes of both plates are $\sim$ 18 mag. We divided the cluster area into concentric circles centered on stars 2244-122 and 2264-245, and measured the density (stars arcmin^{-2}) in the rings. The radii of the clusters were determined by the ring where the star density became indistinguishable from that of the field.

For NGC 2244 a sharp decrease of the star density occurs between radii of 12$'$ and 13$'$ but since no stars with a high probability of membership lie outside this inner radius, we adopted a cluster angular radius of 12$'$. At the distance of the cluster, 1670 pc (Paper I), the radius of 12$'$ is equivalent to 5.83 pc or to a diameter of 11.7 pc.

The model of spherical symmetry around the assumed center applied to NGC 2244 seems to accurately represent its star distribution; however, it fails to portray the structure of the cluster NGC 2264 provided that the brightest star, 2264-245 (S Mon, O7V((f))) is at the center. It is interesting to note that this star seems to be at the center of the bright nebulosity but not at the center of the cluster. Therefore, other considerations need to be made. The nature of the ionization flux from star No. 245 can be traced only in the southern direction, where most of the stars with a high probability of membership are located. This particular elongated shape toward the south direction, with stars No. 245 and 130 at the edges, forms the inverted "Christmas tree" by which this cluster is well-known. Visually, the majority of the stars with P $\geq$ 0.90 are located within an ellipse with a semi-major axis of 25$''$ and with the upper focal point on star No. 245 and the lower one on star No. 130. A detailed analysis of the star distribution around stars No. 245 and 130 reveals that more massive stars, and on the average stars with larger probabilities of membership, are located closer to star No. 245. Since the spectral type of star No. 130 is B1.5V (second brightest in the cluster) the ionizing flux of this star is much smaller than the one for star No. 245. It has been suggested by Schwartz *et al.* (1985) that the ionized rim of the globule at the apex of the Cone Nebula is ionized by star No. 245 rather than by star No. 130 or Allen's (1972) infrared object. Tracing a circle that includes stars No. 245 and 130 and drawing an analogy to the spherical model we can derive a radius of 13$'$ equivalent to 3.6 pc at the assumed distance of 950 pc for the cluster (Paper I). Our estimated cluster center almost coincides with Vasilevskis's *et al.* center at star No. 81. The relevant cluster properties of the clusters under study are described in Table 2. A cross section of the location of the clusters is displayed in Figure 2 with the data and results analyzed in this paper.

c) *Determination of Masses*

We will make use of the bright stars to evaluate cluster masses. By using the index mass number, estimated from the known masses of early-type stars through the formalism presented by Westerlund (1961), Bok (1964) and recently by Pinto (1988), we can obtain lower limits for the masses. Assuming a power law of the form,

$$n(M) = KM^{-(1+x)}, \qquad (1)$$

where $n(M)$ is the number of stars of mass M in a unit of interval of mass, K is constant, and x is an exponent which will be discussed later. Using this stellar mass distribution the cluster mass can be

TABLE 2

SUMMARY OF CLUSTER PROPERTIES

Cluster	NGC 2244	NGC 2264	Notes[a]
α(1950)	06:29.7	06:38.3	1
δ(1950)	04:54	09:56	2
l^{II}	206.4	202.9	3
b^{II}	−2.4	+2.2	4
Height	−70	+37	5
Ang. Diam.	24	26	6
Diam.	11.66	7.20	7
$(m - M_v)$	11.11	9.88	8
Dist.	1670	950	9
$E(B-V)$	0.48	0.06	10
$(B-V)_*$	−0.33	−0.32	11
V	6.73	4.66	12
Type	II 3P	IV 3P	13
Sp. Type	O4V((f))	O7V((f))	14
Vr	+33.7	+20.9	15
OB	34	25	16
T Tauri	300	...	17

a. Notes: (1), (2) Equatorial coordinates for epoch 1950.0; (3), (4) galactic longitude, l^{II}, and latitude, b^{II}, to the nearest degree; (5) Height above or below the galactic plane in pc; (6) apparent angular diameter in arcmin; (7) linear diameter in pc; (8) distance modulus in mag; (9) distance in pc: (10) color excess in mag; (11) turn-up color of the earliest cluster star on the main sequence; (12) apparent magnitude of the brightest member star; (13) Trumpler's cluster classification; (14) earliest spectral type; (15) mean cluster radial velocity, in km s^{-1}, for derivation see text; (16) number of the estimated observable OB-type stars; (17) number of the T Tauri stars candidates, in the range of $17 < V < 22$ mag, observed by Adams, Strom, and Strom (1983).

expressed as (for details of this derivation see Pinto 1988)

$$M_{cl} = \frac{< m >}{< m_* >} \left[\frac{m^x - M^x}{m_*^x - M^x} \right] M_*, \qquad (2)$$

where m, and M are the minimum and maximum cluster stellar masses, m_* is the mass of a well-known early-type star, and $M_* =< m_* > N_*$, where N_* is the number of stars whose mass is greater than m_*.

The index x has generally been assumed to be the Salpeter's (1955) exponent of 1.35. In agreement with this, Sagar *et al.* (1986), from a study of the cluster mass functions, found that an exponent of 1.4 represents the mass index for a sample of young open clusters. In particular, for NGC 2264, Sagar *et al.* (1986), considering moderate mass loss, obtained an index of 1.24. The cluster NGC 2244 was not included in the previous study. Therefore, following the procedure outlined by Sagar *et al.* we pursued this calculation obtaining a very flat mass spectrum index of 0.7, somewhat typical of inner galactic clusters poorly populated by only few massive stars (e.g., NGC 6611, NGC 6823). Thus, both clusters studied appear to be local exceptions to the solar neighborhood initial mass function (IMF) described by Salpeter (1955). In NGC 2264 there are two peaks in the distribution of stars; one for B-type, and the second around K stars (T Tauri stars). Consequently the IMF is bimodal, a conclusion already drawn by Walker (1956). Herbig (1954) also noted a second peak for Hα emitters, mostly T Tauri stars, around apparent magnitudes 15 and 16. Furthermore, in a study of low-mass stars in NGC 2264 Cohen and Kuhi (1979)

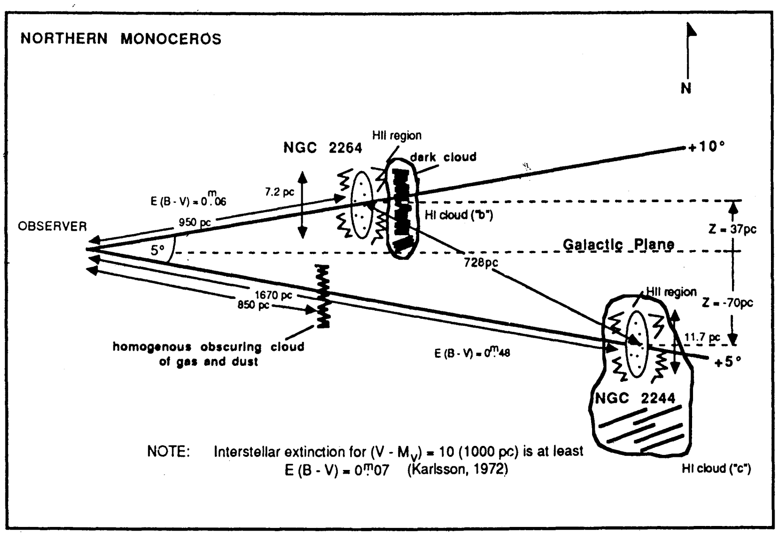

Fig. 2. Cross section (not at scale) of the spatial location of the clusters NGC 2244 and NGC 2264.

found different mass indices from samples of stars with emission (x =2.9) and without emission lines (x =1.7).

The bimodal anomalies of the IMF have recently been discussed by Lårson (1986), although common evidences for such irregularities are known to be present in much larger stellar systems (globular clusters, stellar associations, galactic halo stars, etc.) with one peak due to the arm population and the other due to the interarm population. Along the same line, a further step can be suggested; considerable evidence exists that the sites and triggering mechanisms of low and massive star formation differ both in space and time, although, the observed star formation is an average over giant molecular cloud scales and lifetimes and almost a universal IMF results (Silk 1985).

In NGC 2244 our star sample is too small to be statistically significant and to permit further conclusions. Terlevich (1982, 1985), however, suggests that the slope of the IMF is a strong function of metallicity, i.e., the larger x becomes, the larger the metallicity, where x =1.35 corresponds to 0.2 times the solar metallicity.

For NGC 2244 the latest member star is a B6V, which yields m_* of 5.8 $M_\odot$. It is well-known that no late-type stars are cluster members; therefore we will allow for some undetected stars assuming m = 4.0 $M_\odot$ and M = 61.1 $M_\odot$ which corresponds to star 2244-203 (Paper II). From Paper IV we derived N_* = 27. By using equation (2) with x =0.7 and the Salpeter's exponent (x =1.35) the derived cluster masses are 512 and 441 $M_\odot$. Since binaries are known to be present we will apply a correction factor of 1.5 to the cluster stars to account for unresolved companions (Leonard 1988). After this correction, we obtain 770 $M_\odot$ for x =0.7. By a way of comparison, we must mention that the straightforward sum of the masses of 27 cluster members yield a value of 560 $M_\odot$, considering binaries. Raimond (1966) indicated that the integrated mass of the observed stars was 400 $M_\odot$ for the cluster and 900 $M_\odot$ for the entire association. In adding invisible stars he estimated that the actual masses were at least 1000 to 6000 $M_\odot$, respectively. Assuming a cluster volume of 830 pc^3 and a mass of 770 $M_\odot$, we derive a stellar density of 0.93 $M_\odot pc^{-3}$ for the cluster.

In the case of NGC 2264, we will arbitrarily assume m_* = 2.90 $M_\odot$ corresponding to the spectral type A0V. Likewise, the maximum mass is 44.4 $M_\odot$ for 2264-245, N_*=26, and minimum mass m = 0.6 $M_\odot$, which is the mass of a late K star (data from Paper II and IV). Using the indices x = 1.24, 1.4, and 1.35 (Salpeter's value) we obtain a cluster mass of 380, 416, and 403 $M_\odot$, respectively. Applying the binary correction factor we derive 570 $M_\odot$, for x = 1.24. Earlier estimates of the cluster mass indicated a value of 450 $M_\odot$ (Walker 1956). Blaauw (1964) calculated a total mass, including invisible protostars, of 800 $M_\odot$. Raimond (1966), considering stars hidden in the dark cloud located behind the cluster, gave an upper limit for the mass of 1500 $M_\odot$. A value for the cluster mass of 1000 $M_\odot$ is presented by Lyngå (1981). Other determinations include, Piskunov (1983) with a value of 200 $M_\odot$ and Myakutin, Sagar, and Joshi (1984) who calculated a cluster mass of 282 $M_\odot$. Hence, the stellar mass density, calculated by various authors, ranges from 1.0 to 7.5 $M_\odot pc^{-3}$, assuming a cluster volume of 200 pc^3. It is worth mentioning that the stellar density of both clusters is much larger than the minimum value for a stable configuration (0.09 $M_\odot pc^{-3}$, Trumpler 1938).

IV. CLUSTER KINEMATICS

a) *General Kinematics*

The motion of the cluster NGC 2244 calculated by Riddle (1972), based on stellar proper motions, indicated that it is moving toward negative galactic latitudes. The average proper motion components (all proper motions presented here are per century) for five star members in NGC 2244 are; $< u_\alpha cos(\delta) > = -0.649''$ and $< u_\delta > = -0.467''$. Transforming these components to the galactic coordinates frame we obtain $< u_b > = -0.792''$ and $< u_l > = 0.112''$. It is noted that most of the combined cluster motion of 0.80″ is perpendicular to the galactic plane. Assuming that the motion originated in the galactic plane, the cluster has reached its present distance in an interval of 10^6 yr.

A similar analysis was performed for nine OB-type stars in NGC 2264 by using the proper motions published by Vasilevskis *et al.* (1965). After correcting these averaged values to the LSR reference frame and transforming them to galactic proper motions, we obtained $< u_b > = 0.0137''$ and $< u_l > = 0.1098''$. It is then clear that this cluster is barely moving away from the galactic plane and trailing galactic rotation in a similar fashion as NGC 2244. By the least squares solution in the plane $[b, u_b]$ we can obtain a slope equivalent to du_b/db = 0.165″ per deg per century. Correcting for the spurious contraction in the radial direction amounts to +0.005″ per deg per century, assuming a mean radial velocity of +21.0 km s^{-1}. The coefficient of expansion becomes $du_b/db = 0.001699''$ per deg per year. The kinematic age which accounts for the motion in the galactic latitude, can be estimated as $T = [du_b/db]^{-1} * 3600$ yr, which yields 2.1×10^6 yr in reasonable agreement with other estimates of the cluster age.

We conclude that NGC 2244 is located farther away from the galactic plane (Z = −70 pc) and moving away from it, whereas NGC 2264 seems to be almost stationary and closer (Z = +37 pc) to the galactic plane.

b) *Cluster Radial Velocities from Cluster Members*

In the literature a number of estimates of the radial velocities for cluster members can be found. Selecting stars which are likely to be members from our sample of Paper IV (references therein), we derive mean cluster radial velocities of +33.7±3.0 km s^{-1} from 9 OB stars in NGC 2244 and of +20.9±5.1 km s^{-1} from 9 B stars in NGC 2264. These values are in excellent agreement with estimates obtained by other authors, such as +33.7±2.5 km s^{-1} (Sanford 1949), +34 km s^{-1} (Hagen 1970), +37.2±3.8 km s^{-1} (Riddle 1972), and +33.0±7.0 km s^{-1} (9 stars, Hron 1987, references therein) for NGC 2244, and +21.0 km s^{-1} (Underhill 1958), and +22.0±5.0 km s^{-1} (13 stars, Hron 1987) for NGC 2264.

Under the assumption that the clusters obey the virial theorem, namely $2T+\Omega = 0$, and that they are formed by stars of the same masses, we can find that the dispersion velocity, v_{rms}, is,

$$v_{rms} = 4.63 \times 10^{-2}\,(M/R)^{1/2}\,, \qquad (3)$$

where M is in solar masses and R in pc. For NGC 2244 using R =5.8 pc and M =770 $M_\odot$, we obtain a v_{rms} of 0.533 km s^{-1}. Likewise, for NGC 2264 with R =3.6 pc and M =570 $M_\odot$, we derive a v_{rms} of 0.583 km s^{-1}. These dispersion velocities are typical for galactic clusters and in both cases are smaller than the dispersions obtained from measurements, mainly indicating the lack of accuracy of the latter, although additional forces such as galactic tidal fields or the relevance of encounters cannot be ruled *a priori*. It is known that the escape velocity, v_e, is twice the dispersion velocity, hence $v_e = 2\,v_{rms} = 1.066$ km s^{-1} for NGC 2244 and 1.166 km s^{-1} for NGC 2264.

With the assistance of the cluster radii and the velocity dispersion we can estimate the cluster kinematic ages as 1.0×10^7 yr for NGC 2244 and 6.0×10^6 yr for NGC 2264, the latter value is in excellent agreement with photometric or nuclear age estimates. Although equation (3) presents a weak function of the masses, the derived mass for NGC 2244 for its cluster radius seems too small yielding some unreasonable results. If we used, instead, the mass value suggested by Ogura and Ishida (1981) of 5×10^3 $M_\odot$ we obtain v_{rms} = 1.360 km s^{-1} and a cluster kinematic age of 4.2×10^6 yr in excellent agreement with other estimates.

We must indicate that, assuming a Maxwellian distribution of the stellar velocities, the fraction of stars in a spherical cluster with $v > v_e$ is 0.0074 (Chandrasekhar 1943), and considering that the escape probabilities are very slim for massive stars, even if star samples were large, it is likely that none of their original massive members have escaped from the clusters studied. We must mentioned that this hypothesis has recently been questioned under the light of new studies of runaway B-stars (Conlon 1990) where the majority of them presumably are originated from cluster ejection.

c) *Radial Velocities Derived from the Galactic Rotation*

Since the galactic latitudes of both clusters are ~ 205 degrees, radial velocities derived from the galactic rotation will be somewhat significant. Using the formula that describes the local galactic rotation in terms of the radial velocity (in km s^{-1}) we see,

$$Vr = \left[(R_\odot/R)\theta(R) - \theta(R_\odot)\right] sin(l^{II})\, cos(b^{II}), \qquad (4)$$

where $R_\odot$ = 10 kpc, R in kpc and $\theta(R)$ is the circular velocity around the galactic center. Although, a new solar galactic distance, of 8.5 kpc, and the solar rotation velocity around the galactic center, of 220 km s^{-1}, have been approved by the IAU Commission No. 33 in 1985, we will use the previous determinations because the formulae are calibrated for such values. According to Burton (1971), $\theta(R)$, in km s^{-1}, can be written as (valid for 10 kpc $\leq R \leq$ 14 kpc),

$$\theta(r) = 885.44\,R^{-1/2} - 30000\,R^{-3}\ . \qquad (5)$$

Using a variation of the theorem of cosine we obtain values of the cluster through the equation,

$$R^2 = R_\odot^2 - 2\,dR_\odot\, cos(l^{II})\, cos(b^{II}) + d^2, \qquad (6)$$

where d represents the cluster distances and the other symbols have the conventional meaning. Hence, we obtain the galactic distances, R, as 11.52 and 10.88 pc for NGC 2244 and NGC 2264, respectively, provided that the cluster distances, d, are the ones presented in Paper I. The derived values of the cluster mean radial velocities with respect to the local standard of rest, Vr_{LSR}, are 18.0 km s^{-1} for NGC 2244, and 9.6 km s^{-1} for NGC 2264. Riddle (1972) estimated the mean Vr_{LSR} for NGC 2244 as 21±3 km s^{-1}. A further calculation of the solar reflex motion toward these clusters yields values of 16.2 km s^{-1} for NGC 2244 and 15.0 km s^{-1} for NGC 2264. These estimates were obtained using the standard solar motion velocities presented in Mihalas and Binney (1981). Consequently, the cluster radial velocities can be entirely explained in terms of galactic rotation plus solar motion. Such values are 34.2 km s^{-1} for NGC 2244 and 24.6 km s^{-1} for NGC 2264, strikingly similar to the observed mean cluster radial velocities previously described.

d) *Location of the Clusters in the Galactic Plane*

The seminal work of Trumpler (1930) and the subsequent conclusive study of Morgan, Sharpless, and Osterbrock (1952) showed that the space distribution of open clusters outlined spiral arms. It is also known that OB-type stars are spiral-arm tracers. Studying this class of stars McCuskey and Houk (1964) found that at this galactic longitude they are chiefly concentrated in a region between 1 and 3 kpc.

Employing the cluster distances determined in Paper I, namely 1670 pc for NGC 2244 and 950 pc for NGC 2264, we place the clusters within the Galaxy. The galactic latitudes and longitudes are listed in Table 2. We have plotted the cluster locations in Figure 3 along with open clusters with known ages and galactic heights of less than 150 pc taken from the catalog of Lyngå (1981). No clear trace of spiral arms is found. In Figure 4, we have narrowed down our sample considering only clusters with ages, t_{age}, of $\leq 4\times10^7$ yr. A weak distinguishable structure is present and some delineated filaments start to appear. Finally, clusters with ages of $\leq 10\times^7$ yr are plotted in Figure 5. The three spiral arms, in the right upper corner, Perseus arm, in the center the Local arm (Orion-Cygnus), and below the Sagittarius-Carina arm are barely visible. A similar conclusion was recently pointed out by Hron (1987) and Janes, Tilley, and Lyngå (1988) from studying an extensive sample of open clusters. Nevertheless, this can be an artifact due to the irregular effects of interstellar extinction.

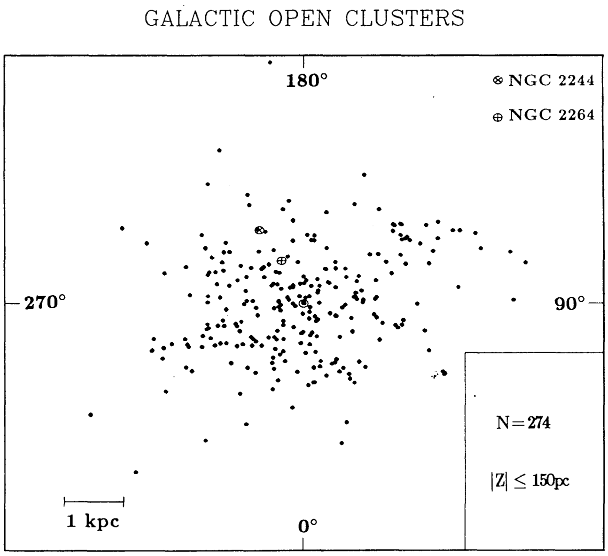

Fig. 3. Distribution of galactic open clusters in the galactic disk, for clusters classified with spectral types O and B in the catalog of Lyngå (1981). Note that the expected spiral structure is unnoticeable.

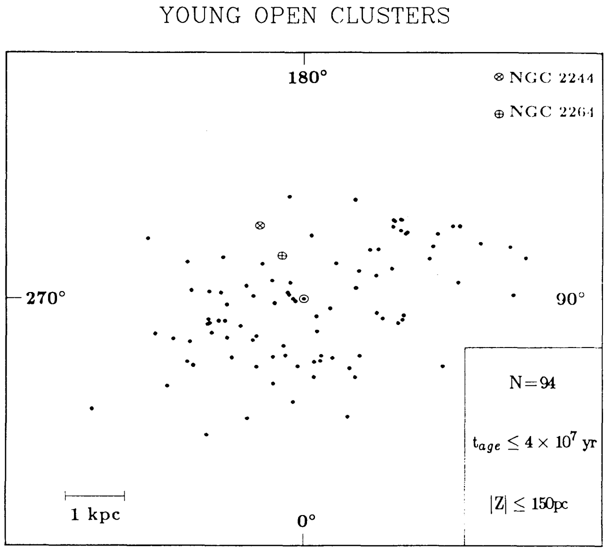

Fig. 4. Same as Figure 3, but for clusters of age $\leq 4 \times 10^7$ yr.

From the locus of the local arm, which extends up to 1 kpc, it is clear that the cluster NGC 2264 is located on its outer edge, whereas NGC 2244 is located at the external region of the Perseus arm (Riddle 1972; Guseva *et al.* 1985). It is interesting to note that the young clusters NGC 6383, 6530, and 6611 are located in the inner spiral arm as seen in Figures 3, 4, or 5, indicating the direction of the galactic rotation (based on their radial velocities of −2.0, −11.0 and +23.0 km s^{-1}, from Hron 1987) and clearly delineating the Sagittarius-Carina arm.

V. CLUSTER AGES AND STELLAR FORMATION EFFICIENCIES

a) *Determination of Ages*

Classical determinations of ages of open clusters rely mostly on the application of theoretical isochrones in their H-R diagrams. Such determinations are strongly influenced by the assumptions made about the mode of the stellar formation, e.g., many determinations of age in NGC 2244 use the turn-off points of the evolved massive stars from the main sequence to determine the cluster age. A common

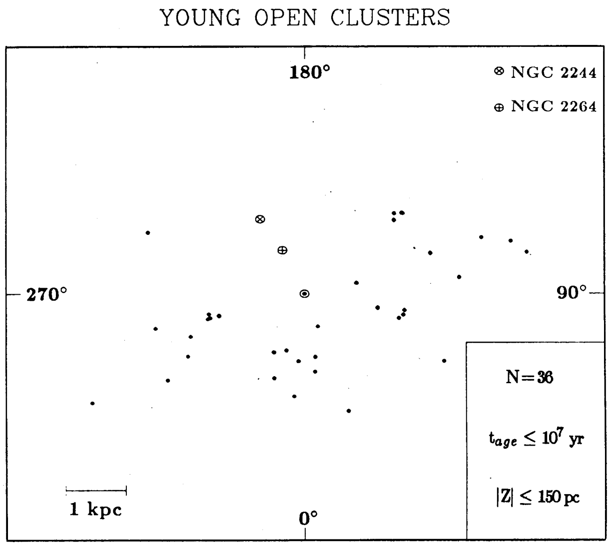

Fig. 5. Same as Figure 3, but for clusters of age $\leq 10^7$ yr.

source of uncertainty comes from the large number of isochrones and consequently poor resolution near the ZAMS. What would happen if the massive stars are not coeval with the rest of stars in the cluster? If we answer positively, then the estimated ages are merely lower limits. Moreover, most theoretical isochrones do not take into account mass loss effects, although new studies have included this correction (Mermilliod and Maeder 1986). A good review of the conventional methods of determining ages in open clusters is given by Sagar (1985). It has also been argued by Strom, Strom, and Yost (1971) that most of the dispersion in the H-R diagram for NGC 2264 is due to the effect of circumstellar shells (CS) rather than age spread. Besides CS, many other data effects (reddening) or stellar intrinsic effects (duplicity, mass loss, rotation, different chemical composition, distances, etc.) are well-known in introducing spurious scattering in the H-R diagram.

Several methods to determine ages use theoretical evolutionary tracks (TET, e.g., Iben 1965) to assign ages to individual stars. This procedure requires extreme care in dealing with objects above the main sequence, since for stars slightly above erroneous PMS ages and star formation rates can result (Stahler 1985). Recently, Schroeder and Comins (1988, SC hereafter), motivated by Stahler's claim, have elaborated a statistical calculation device by which more accurate cluster ages can be obtained. This method considers as main sequence stars all objects lying within a range of $(B-V) = 0.1$ mag of the ZAMS line. We will use this procedure in order to estimate ages for the cluster under study.

In NGC 2244 the range of masses from 24.4 $M_\odot$, corresponding to star No. 84, to 5.8 $M_\odot$(m_* in section III.c) is representative of stars likely to be cluster members. In the nomenclature of SC we define $m_1 = 5.8$ $M_\odot$, $m_2 = 24.4$ $M_\odot$, and the mass spectral index $\gamma = 1 + x = 1.7$. Using the same sample of stars, $N_* = 27$ as in section III.c, we obtain $\Omega(m_1, m_2) = 0.0177$, $C = 8.217\times10^6$ yr and $n(m_1, m_2) \pm \sigma_n = 0.93\pm0.03$ (ratio of the number of stars on the main sequence to the total number of stars in the mass range m_1 to m_2). These quantities are combined in the following formula to calculate the cluster ages,

$$T_\pm = \frac{C\Omega(m_1, m_2)}{[1-(n(m_1, m_2) \pm \sigma_n)]} \ . \qquad (7)$$

The result for NGC 2244 is in the range of 1.45×10^6 to 3.63×10^6 yr with a central value at 2.1×10^6 yr. The calculated range is in good agreement with other age estimates for this cluster.

For NGC 2264 we will introduce a small refinement to the age value presented by SC of 5×10^6 yr. Since the best spectral mass index calculated for this cluster by Sagar *et al.* (1986) is 1.24, slightly smaller than Salpeter's value employed by SC in their calculation, we will use this index value. We use the mass bin from SC of 2.25 to 9.0 $M_\odot$ with $n(m_1, m_2) \pm \sigma_n = 0.64\pm0.09$ to obtain $\Omega(m_1, m_2) = 0.153$ and $C = 12.482\times10^6$ yr. From equation (7) we obtain a range of ages from 4.24×10^6 to 7.10×10^6 yr, with a central value at 5.3×10^6 yr. Therefore, the derived ages are a weak function of the mass index since our result is similar to the one obtained by SC. We must comment that the age estimated for NGC 2264 is typical of the mass interval (2.25–9.0 $M_\odot$) used, where only a small number of stars are known to be members. An ideal case would be to include a lower mass limit; however, it is difficult to achieve completeness in a low-mass star sample. We estimate that in the event of considering a larger sample of masses, the cluster age would be larger, in agreement with recent estimates of Sagar *et al.* (1986) of 10^7 yr and Lyngå (1981) of 2×10^7 yr, although, Mermilliod (1981) assigned a cluster age of $\sim 3\times10^6$ yr and situated it in the age group of NGC 6231, Orion Nebula cluster, and NGC 6383.

A comparison of our earlier estimates of cluster masses (770 $M_\odot$ for NGC 2244 and 570 $M_\odot$ for NGC 2264) and ages seem to be in good agreement with the empirical calibration obtained by Pandey, Bhatt, and Mahra (1987) which states that younger clusters have higher masses for cluster ages smaller than 10^8 yr.

b) *Stellar Formation Efficiency (SFE)*

A parameter of great interest is the stellar formation efficiency (SFE) in the study of young associations. This figure is strongly affected by extinction and incompleteness of the stellar sample. Consequently the estimated values can only be considered lower limits of the true SFE. In a study of star-forming regions Cohen and Kuhi (1979) estimated an overall efficiency (calculated as the ratio of mass observed in stars to total gas mass for the entire region) of about 10%, a value slightly overestimated according to the molecular masses involved in their calculation.

We will consider the SFE as the ratio of,

$$SFE = M_{cluster}/M_{Total}\ , \qquad (8)$$

where M_{Total} in the most complete sense is $M_T = M_{cluster} + M_{HI} + M_{HII} + M_{dust} + M_{clouds}$.

The SFE of the cluster NGC 2244 has been studied with certain detail by several authors. Ogura and Ishida (1981) assuming $M_{cluster} = 5\times10^3$ $M_\odot$ (this mass value seems reasonable for the whole association Mon OB2), obtained an efficiency of 22%. Including the mass in dust form (Celnik 1983b), the total mass becomes $M_T = 3.1\times10^5$ $M_\odot$ with the values taken from Section III.a. Hence, we obtain a much lower SFE of ~ 1.6%.

An analogous result is obtained for NGC 2264 by using a mass value for the whole association Mon OB1 of $M_{cluster} = 1500$ $M_\odot$ (Raimond 1966), and including the mass in molecular and H I clouds, $M_T = 4.0\times10^4$ $M_\odot$, leads to a SFE of ~ 3.8%. The latter value is an upper limit for the SFE since no estimates are known for M_{HII} and M_{dust} in Mon OB1. Crutcher *et al.* (1978) quoted a SFE of 3%. The SFE values obtained are somewhat typical of regions with extended H II regions; in contrast, cold clouds appear to have higher SFE and less massive stars (Genzel 1987) (e.g., ρ Oph has a SFE in the range of 34% to 47%, Wilking and Lada 1983).

The suggestion by Pandey *et al.* (1986) that there is a decreasing trend of the total cluster masses with age implies that the SFE and initial formation rate of rich clusters are also decreasing with time, a conclusion which cannot be conclusively rejected or confirmed with our results.

VI. DISCUSSION

The regions around the clusters NGC 2244 and NGC 2264 appear to be entirely different; their past histories have probably also been quite distinct. One of the similarities, however is that both clusters are embedded and surrounded by extensive neutral and molecular clouds, although NGC 2244 is far more massive. A comparison of the dark cloud complexes in the cluster regions suggests that the two are qualitatively different and that the dominant star formation mechanisms are different.

The central hole of the Rosette Nebula, where the cluster NGC 2244 is located, seems to be a relic of the rapid collapse of material into the cluster stars (Fountain *et al.* 1979). In this picture, the central hole is being filled by expansion of the ionization fronts from the nebula. The finding by Meaburn and Walsh (1986) of ionized knots driven by an expanding shell, resembling Herbig-Haro (HH) objects, indicates that these are either by-products of massive stellar formation or that low-mass star formation may be taking place now. If these knots are positively identified as HH objects due to their small ages, $t_{age} << 10^6$ yr (Adams, Strom, and Strom 1979), the entire history of stellar formation in this cluster must be re-assessed. (It is interesting to note that these small condensations were already visible on the plates of the Palomar Sky Survey). The scenario of a rapid stellar formation in NGC 2244, restricted to a single episode, explains the observed low dispersions in masses, ages, relatively small infrared excesses and variabilities in the cluster sample. From theoretical models of the IMF it has been predicted that mass spectrum indices of about $x \sim 0.5$ correspond to cloud collision mechanism and for $x \simeq 1$ to 1.3 to cloud fragmentation (Burki 1980). The comparison with these models and the mass spectrum index of 0.7 obtained for this cluster in Section III.c, reinforces the idea of the cluster originating in the collision of clouds, a mechanism also supported by Blitz (1980) and Guseva *et al.* (1985).

Due to the proximity of NGC 2264 to the supernova remnant the Monoceros Loop, it is tempting to suggest that a related explosion triggered star formation; however, this hypothesis is untenable if the age of the Monoceros Loop is considered to be $t_{age} > 1.5\times10^5$ yr (Wallerstein and Jacobsen 1976). Nevertheless, studying the morphology and characteristics of the expanding shells present in Mon OB1, Herbst (1980) found that these shells are similar to the ones produced by either supernova explosions or by *UV* photons and stellar winds from O stars. But since O stars become supernovae it is difficult to avoid having a supernova involved in the formation of these shells. From the diversity of the mass spectrum indices calculated for this cluster which range from $x \simeq 2.9$ (Cohen and Kuhi 1979) to 1.24 (Sagar *et al.* 1986), for different group of stars, and a comparison with the models listed by Burki (1980) we suggest that the mechanism responsible for the cluster formation is not unique. From the overall cluster value of $x = 1.24$, the mechanism of cloud fragmentation is indicated (Burki 1980). Nevertheless, there are some theoretical indications which support the idea that fragmentation would most likely trigger star formation of low-mass stars (Silk 1978).

The term of extreme Population I (mostly O-B2) clearly describes the cluster members in NGC 2244. Similarly, the term normal and late Population I represents the early group of cluster members in NGC 2264 (B3-B8, and early-A). and the T Tauri stars.

VII. CONCLUSIONS

In summary, with the new cluster data and methods presented in the recent literature, we have recalculated some of the basic properties of the cluster NGC 2244 and NGC 2264. Our results, with the inclusion of some refinements, are in good agreement with some previous estimates.

We suggest that the current episode of star formation in the Rosette Nebula may have been triggered by the ultraviolet radiation of the O stars. The cluster NGC 2244 seems more kinematically active than NGC 2264 which is also older and closer to the sun. This may imply that a more energetic triggering mechanism is responsible for the star formation in NGC 2244. In term of masses, the molecular abundance in the neighborhood of NGC 2244 is one order of magnitude larger than in NGC 2264 probably enhancing its youth or suggesting a more massive origin.

The cluster origins appear consistent in the case of NGC 2244 and are attributed to cloud collisions, however, for NGC 2264 this mechanism is not unique and is not entirely understood at present. There are few evidences that a supernova explosion could be the originating mechanism in the Mon OB1 association. In addition, for NGC 2264 the overall mass spectrum index of 1.24 seems to suggest that cloud fragmentation may play an important role in the formation of the cluster. This explains the presence of a large number of T Tauri stars in the cluster field. The intense emissions and winds of the O and B stars may have helped to dissipate the cloud fragments.

Both clusters confirm the observation by Lada (1980) that OB star formation preferentially occurs at the edges and not at the centers of large molecular clouds. Nevertheless, unlike other regions, the clusters studied do not support the model of sequential formation of OB associations proposed by Elmegreen and Lada (1977). In order to better understand the large-scale structure of the region higher spatial resolution studies of the molecular clouds are necessary and on the small-scale, the detection of compact radio sources and stellar molecular outflows seem inevitable.

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