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FUNDAMENTAL PARAMETERS OF NGC 2509 BASED ON 2MASS DATA

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ABSTRACT

A deep stellar analysis is introduced for the poorly studied open cluster NGC 2509. The Near-IR database of the digital Two Micron All Sky Survey *(2MASS)* has been used to re-estimate and refine the fundamental parameters of the cluster, i.e. age, reddening, distance, and diameter. As well as, luminosity function, mass function, total mass, relaxation time, and mass segregation of NGC 2509 have been estimated here for the first time.

Key words : Galaxy: open clusters and associations — individual: NGC 2509 — astrometry — Stars: luminosity function — Mass function — Stars: Kinematics

I. INTRODUCTION

NGC 2509 (*OCl* 630, *Mel* 81) is situated in the northern Milky Way at 2000.0 coordinates $\alpha = 08^h\ 00^m\ 48^s$, $\delta = -19^\circ\ 03'\ 06''$, $\ell = 237^\circ.84$, $b = +05^\circ.84$. It is placed in the direction of the Puppies constellation; on the Orion arm of the Galaxy. Fig. 1 represents the blue image of NGC 2509 as taken from Digitized Sky Surveys *(DSS)**

Charlier (1918), Trumpler (1930), Collinder (1931), and Barhatova (1950) estimated the distance of the cluster to be 1130, 3050, 2700, and 1820 pc respectively. Melotte (1915) and Barhatova (1950) identified the angular diameter of NGC 2509 to be 4.0 and 10.0 arcmin respectively. On the other hand, Ruprecht (1966) classified this cluster as *II-1-p* in the Trumpler classification system, while the membership were estimated to be 56 and 30 stars by Raab (1922) and Collinder (1931) respectively.

Later, two recent papers have been published for the cluster under consideration. Ahumada (2000) presented *BVRI* CCD observations of NGC 2509. The age, reddening, distance modulus, and metal content are estimated to be 1 Gyr, 0.22 mag, 11.79 mag (2300 pc), and 0.02 respectively. Although the cluster's diameter is obtained as 8.0 arcmin, according to Lyngå† (1987), it has been mentioned in Table 1 of Ahumada (2000) as 12.0 arcmin (maybe it was a typo error !). However, Ahumada selected 274 stars for his acceptable fitting with determining a diameter of 6.0 arcmin, which is in agreement with *WEBDA*‡ database.

On the other side, Sujatha & Babu (2003) presented *UBVRI* CCD photometric observations of the open cluster NGC 2509. The age, reddening, and distance modulus are estimated to be 8 Gyr, 0.15 mag, and 9.8 mag (912 pc) respectively. They selected 96 stars for their fitting without defining any diameter for the cluster ! Finally they concluded that the open cluster NGC 2509 is old enough, hence it is unsuitable for tracing the spiral arm of the Galaxy.

This paper is organized as follows. In Sect. 2, the astrometry is introduced with determining the cluster center and radii. In Sect. 3, the photometry is presented with estimating the luminosity and mass functions, as well as the total mass, relaxation time, and mass segregation are obtained. Finally, the conclusions have been summarized and listed with a comparison table in Sect. 4.

II. THE ASTROMETRY OF NGC 2509

The Two Micron All Sky Survey *2MASS*§ has proven to be a powerful tool in the analysis of the structure and stellar content of open clusters (cf. Bonatto & Bica 2003, Bica et al. 2003). It is uniformly scanning the entire sky in three near-IR bands $J(1.25\ \mu\text{m})$, $H(1.65\ \mu\text{m})$ and $K_s(2.17\ \mu\text{m})$ with two highly automated 1.3-m telescopes equipped with a three channel camera, each channel consisting of a 256×256 array of HgCdTe detectors. The photometric uncertainty of the data is less than 0.155 mag with $K_s \sim 16.5$ mag photometric completeness. Further details can be found at the *2MASS* web site. From Soares & Bica (2002), we can see that the errors are more affected for K_s at given magnitude. So that, J and H data have been used here to probe the fainter stars of NGC 2509 with smaller errors.

In order to maximize the statistical significance and representativeness of background star counts, an external ring (the same area of the cluster) has been used as offset field sample. This external sample lies at 1 degree away from the cluster's center in Northern declination.

* *http://cadcwww.dao.nrc.ca/cadcbin/getdss*
† *http://vizier.u-strasbg.fr/cgi-bin/VizieR-4*
‡ *http://obswww.unige.ch/webda/navigation.html*
§ *http://www.ipac.caltech.edu/2MASS*

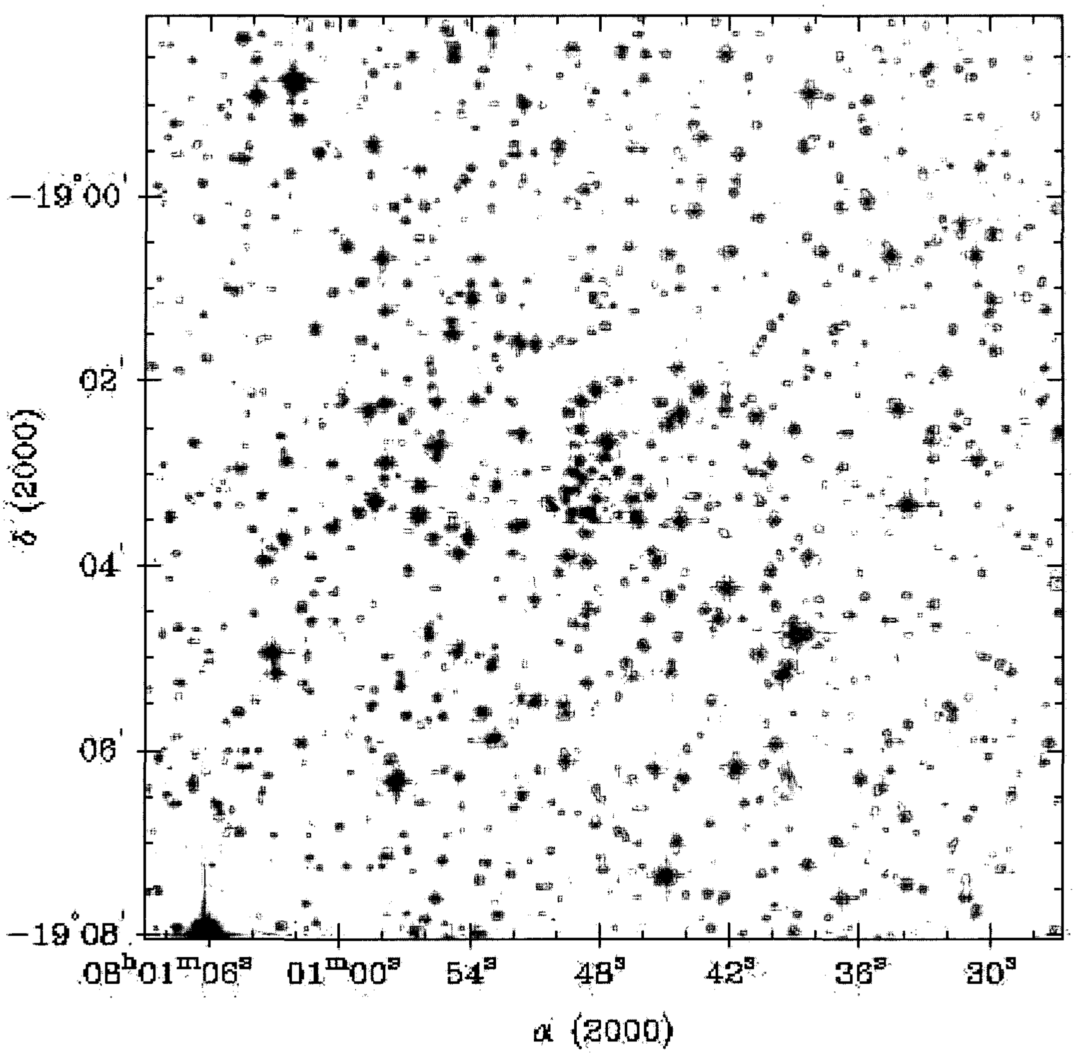

Fig. 1.— The blue image of NGC 2509 as taken from Digitized Sky Surveys *(DSS)*. North is up, east on the left.

Before counting stars, we applied a cutoff ($J < 16.0$) to both cluster and offset field to avoid over-sampling, i.e. to avoid spatial variations in the number of faint stars which are numerous, affected by large errors, and may include spurious detections (Bonatto et al. 2004). The background contribution level corresponds to the average number of stars included in the offset field sample is found to be 3.5 stars per arcmin^2.

On this respect, the number of stars in the direction of NGC 2509 within a preliminary radius of 20 arcmin turns out to be 4500, compared to 3870 in its offset field. Stars extraction have been performed using the known tool of *VizieR*¶. Because of the weak contrast between the cluster and background field density, some inaccurate statistical results maybe produced beyond the real limit of the cluster border.

(a) The Cluster Center

The cluster center is define as the location of maximum stellar density of the cluster's area. The cluster center is found by fitting Gaussian to the profiles of star counts in right ascension (α) and declination (δ), as shown in Fig. 2. Using this method (cf. Tadross 2004, 2005), the estimated center is found to be lie at α = 120.17417 ± 0.006 and δ = -19.07122 ± 0.004 degrees. This center is found to differ from what obtained in *WEBDA* site by 6 sec in right ascension, and 70 arcsec in declination; which is in agreement with what

¶ *http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=2MASS*

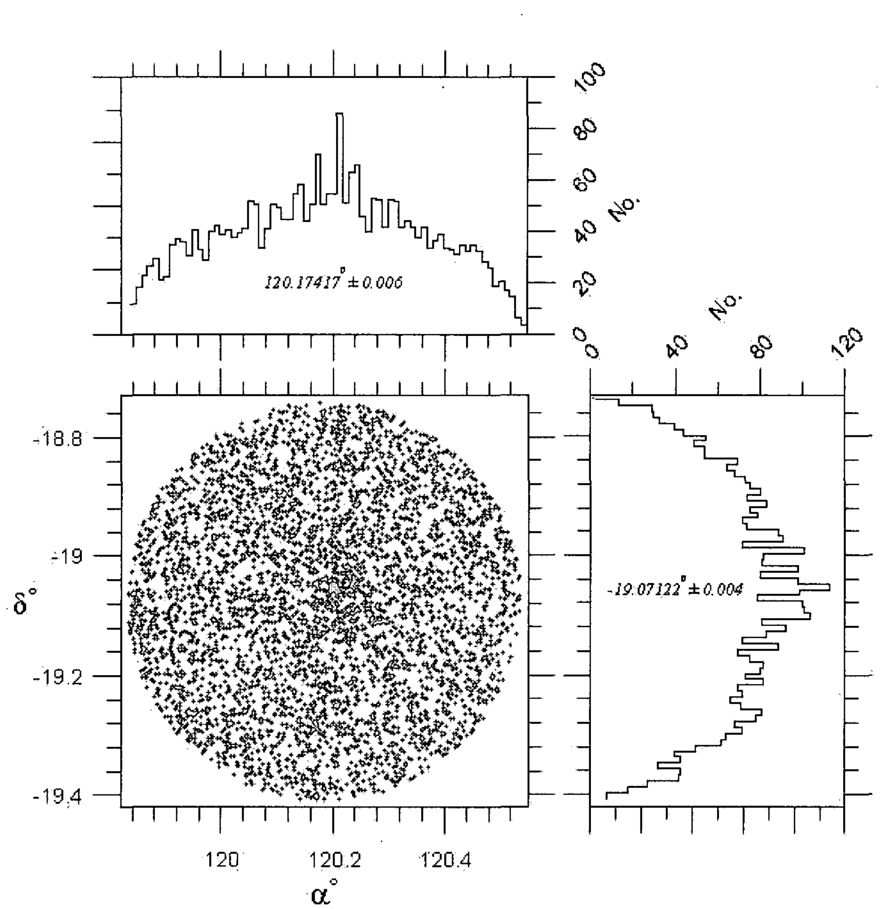

Fig. 2.— Profiles of stellar counts across NGC 2509. The Gaussian fits have been applied to the right ascension (α) and declination (δ) profiles. The center of symmetry about the peaks of the two profiles is taken to be the position of the cluster center.

obtained in *SIMBAD*[||].

(b) The Cluster Radii

To determine the cluster radii of NGC 2509 (border, core, and tidal radii), the radial surface density of the stars $\rho(r)$ should be achieved firstly. The tidal radius determination is made possible by the spatial coverage and uniformity of *2MASS* photometry, which allows one to obtain reliable data on the projected distribution of stars for large extensions around clusters (Bonatto et al. 2005). In this context, the cluster area has been divided into a number of concentric circles (zones) out to the preliminary radius of 20 arcmin. The number density of stars, ρ_i, in the ith zone has been calculated as $\rho_i = N_i/A_i$, where N_i is the number of stars and A_i is the area of the ith zone (cf. Tadross 2005). Applying the empirical profile of King (1962), which given for an open cluster as:

$$\rho(r) = \rho_0 \left\{ \frac{1}{\sqrt{1+(r/r_c)^2}} - \frac{1}{\sqrt{1+(r_t/r_c)^2}} \right\}^2$$

to the surface density profile. In this equation, r_c is the cluster core radius and defined as the radial distance at which the value of $\rho(r)$ becomes half of the central density ρ_o, and r_t is the tidal radius where the cluster disappears. The tidal radius depends on both the effect of the Galactic tidal field on the cluster and the subsequent internal relaxation and dynamical evolution of the cluster (Allen & Martos 1988).

The real cluster border is defined at that point which covers the cluster area and reach enough stability in the density of the background, i.e. the difference between the observed density profile and the background one is almost equal zero (cf. Tadross 2004). The radial distribution of stars in NGC 2509, as shown in Fig. 3, indicates that the extent border of the cluster can reach 8.0 arcmin because of the extended halo, this value is in agreement with Lyngå(1987). The value of the core

[||] *http://simbad.u-strasbg.fr/sim-fid.pl*

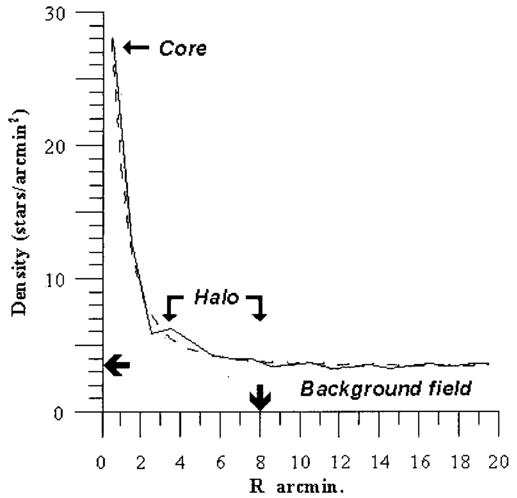

Fig. 3.— Radial distribution of surface star density for NGC 2509 (solid line). The horizontal arrow marks the average background level of the offset field. Poisson errors can be neglected because the large number of stars in each bin. The surface density profile is fitted to the radial distribution of the stars (dashed line). The vertical arrow marks the limited border of the cluster.

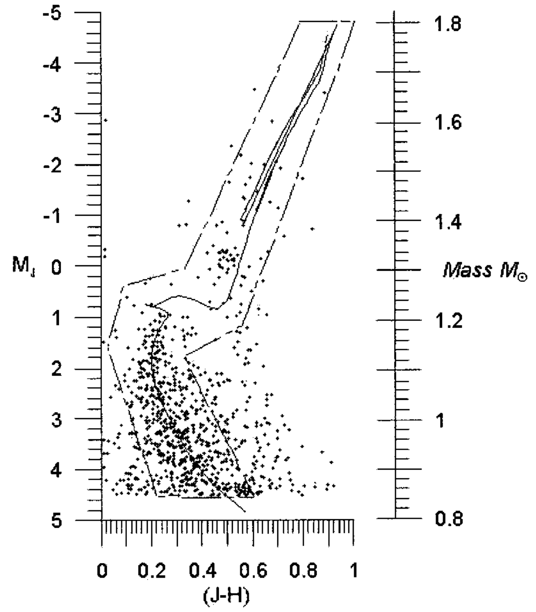

Fig. 4.— Padova solar isochrones with age of 6.1 Gyr is fitted to the $J \sim (J-H)$ *CMD* of NGC 2509, resulting in $E(J-H) = 0.00$, and $(m-M)_o = 11.50 \pm 0.10$ mag, corresponding to a distance of 2000 ± 85 pc. Representative mass scale is indicated in the right side of the figure. The dashed line shows the color and magnitude filters used in reducing the field contamination of the cluster.

radius derived in this way is found to be 1.5 arcmin.

III. THE PHOTOMETRY OF NGC 2509

Because of the lower galactic latitude of NGC 2509, the background field of the cluster is found to be crowded ($\approx$ 3.5 stars per arcmin^2), and the observed color-magnitude diagram (*CMD)* is contaminated. In order to reduce the effect of this contamination, many stars, which introduce some noise in the photometry should be carefully subtracted. In this context, the consequences of having applied color and magnitude ($J < 16.0$) filters to the *CMD* have been examined (Bonatto et al. 2005), as shown in Fig. 4. Therefore, 660 member stars are found inside the limited border of the cluster (R $\leq$ 8 arcmin). This number is large enough for giving statistically significant results.

Depending on the depth of the *2MASS* photometry, the fundamental parameters of the cluster (age, reddening, distance modulus, and metal content) can be determined simultaneously, in precision way, by fitting isochrones to the *CMD* of the cluster. In this respect, several fittings have been applied on the $J \sim (J-H)$ of NGC 2509 using Bonatto et al. (2004) solar metallicity "Padova" isochrones of different ages. These isochrones are fitted to the lower envelope of the points matching the main sequence, turn-off point, and red giant positions, Fig. 4.

$R_V = 3.2$, $A_J = 0.276 \times A_V$, and $E(J-H) = 0.33 \times E(B-V)$ have been used for reddening and absorption transformations, according to Dutra, Santiago & Bica (2002) and references therein. The overall shape of the *CMD* is found to be well reproduced with isochrones of age = 1.6 Gyr. Accordingly, the distance modulus turns out to be $(m-M)_o = 11.50 \pm 0.10$ mag, with zero reddening, corresponding to a distance of 2000 ± 85 pc. Consequently, the distances of the cluster from the galactic plane, Z, from the galactic center, R_g, and the projected distances on the galactic plane from the Sun, $X_\odot$, $Y_\odot$, are found to be 203 pc; 9.7, −1.7 and 1.1 kpc respectively. In this respect, the values of the limited border, core, and tidal radii of NGC 2509 are estimated to be 4.6, 0.90, and 14.0 pc respectively as well.

(a) Luminosity Function *(LF)*

The observed stars have been counted in terms of the absolute magnitude M_J after applying the distance modulus derived above. The color and magnitude filters cutoffs have been applied to the cluster and offset field. The magnitude bin interval are taken to be $\Delta M_J = 0.50$ mag. This size interval is selected so as to include a reasonable number of stars in each bin and for the best possible statistics of the luminosity and mass functions. In Fig. 5, the *LF* (shaded area), constructed as the difference in the number of stars in a given magnitude bin between the cluster (solid line) and offset field (dashed line). The scale of observed J magnitude appears along the upper axis of Fig. 5. From the *LF*

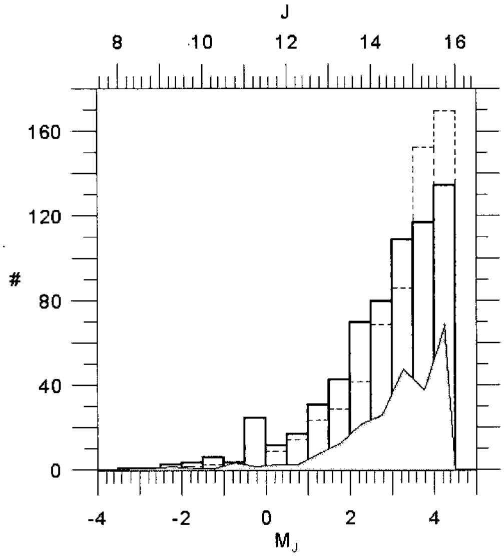

Fig. 5.— Spatial distribution of luminosity function for NGC 2509 in terms of the absolute magnitude M_J. The color and magnitude filters cutoffs have been applied to the cluster (solid line) and the offset field (dashed line). Shaded area represents the background subtracted *LF*. The scale of observed J magnitude appears along the upper axis.

of NGC 2509, we can infer that more massive stars are more centrally concentrated and the beak value lies at fainter, low masses (Montgomery et al. 1993).

(b) Mass Function *(MF)*, and Total Mass

The stellar initial mass function *IMF* is defined as the density of stars per unit mass bin, and represented as:

$$\Psi(M) = \frac{dN}{dM}$$

The *IMF* for high-mass stars ($> 1\,M_\odot$) has been established and well studied by Salpeter (1955). He derived the *IMF* from the luminosity function of the present day field stars assuming a constant rate of star formation and correcting for stellar evolution. In linear units Salpeter's function is given by:

$$\Psi(M) \propto M^{-\alpha}$$

where $\alpha = 2.35$ for stars in the mass range 1–10 $M_\odot$. The steep slope of the *IMF* indicates that the low-mass stars is greater than the high-mass ones. In the present work, the masses have been estimated for the cluster members by using the stellar mass-luminosity relation taken from the 1.6 Gyr solar metallicity "Padova" isochrone (Bonatto et al. 2004). In this sense, two polynomial equations of second degrees have been used for two ranges of stars luminosities as following:

$$\mathrm{M}/M_\odot = 1.8 - 0.01\ \mathrm{M}_J - 0.0025\ \mathrm{M}_J^2 \quad (\text{-}5 \le M_J < 1),$$

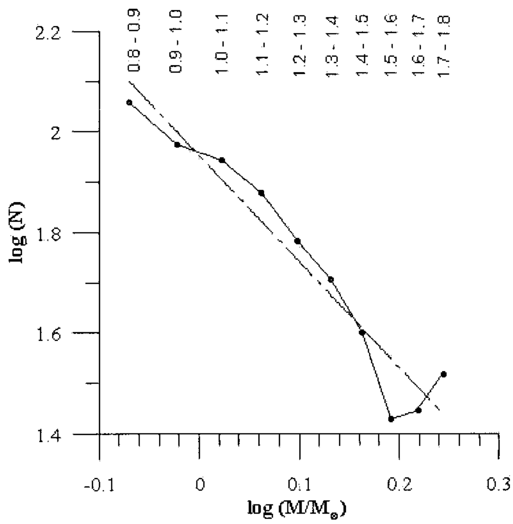

Fig. 6.— The mass function of NGC 2509. The slope of the initial mass function *IMF* is found to be $\Gamma = -2.40 \pm 0.07$; with correlation coefficient of 0.95. The limits of the bins in solar masses are indicated above.

$$\mathrm{M}/M_\odot = 2.05 - 0.32\ \mathrm{M}_J + 0.01\ \mathrm{M}_J^2 \quad (1 \le M_J < 9).$$

A scatter-plot has been constructed for the cluster stellar masses showing the number of stars at 0.5 intervals between 0.8–2.0 $M_\odot$. Using a least-squares fit, the slope of the *IMF* is found to be -2.40 ± 0.07, as shown in Fig. 6. This value is in good agreement with what given by Salpeter (1955), whereas the most stars of NGC 2509 concentrated in the mean mass bin of 0.85 $M_\odot$. In this respect, the total mass of the cluster has been estimated by summing up the stars in each bin weighted by the mean mass of that bin. It yields a direct cluster mass of $\sim 800\,M_\odot$. For the sake of precision, more conservative total mass can be given by applying the equation of Jeffries et al. (2001),

$$R_t = 1.46\ M_c^{1/3}$$

where, R_t and M_c are the tidal radius and total mass of the cluster respectively. The estimated total mass is found in good agreement with the pervious one.

(c) Mass Segregation, and Dynamical State

The evidence for mass segregation in a cluster may be seen from a plot of radius against the mass range of the cluster members. It is visible as a decrease of stars on the outer side of the cluster. For a dynamically relaxed cluster, the higher mass stars are expected to be settled toward the cluster center, while the fainter, lower mass stars are residing in the outer regions of the cluster, Mathieu (1984). One would like to know whether existing mass segregation is due to dynamical evolution or imprint of star formation process.

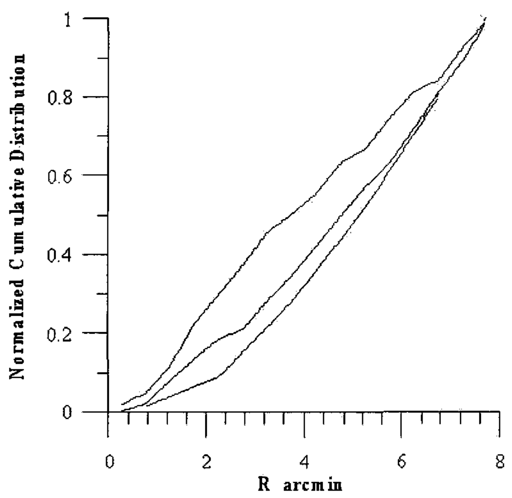

Fig. 7.— Mass segregation in NGC 2509. Moving from left to right, the curves represent the mass ranges $M/M_{\odot} >$ 1.5, $1.0 \leq M/M_{\odot} \leq 1.5$, and $M/M_{\odot} < 1.0$. This indicates that the bright massive stars accumulate much more quickly with radius than the fainter low mass stars do.

At the time of formation, the cluster may have a uniform spatial stellar mass distribution, which may be modified due to dynamical evolution of the cluster members. Because of dynamical relaxation, low mass stars in a cluster may possess largest random velocities, trying to occupy a large volume than the high mass stars do (cf. Mathieu & Latham 1986, McNamara & Sekiguchi 1986, Mathieu 1985). To display mass segregation in NGC 2509, star counts are performed on all members as a function of distance from the cluster center and masses. The results are given in Fig. 7. The individual curves moving from left to right are for mass ranges $M/M_{\odot} >$ 1.5, $1.0 \leq M/M_{\odot} \leq 1.5$, and $M/M_{\odot} < 1.0$. It suggests that the brighter high mass stars concentrate towards the cluster center and accumulate much more quickly than the fainter low mass stars do.

On the other hand, to know if the cluster reached the dynamical relaxation or not. The dynamical relaxation time, T_R is the time in which the individual stars exchange energies and their velocity distribution approaches a maxwellian equilibrium. It is given by

$$T_R = \frac{8.9 \times 10^5 N^{1/2} R_h^{3/2}}{< m >^{1/2} log(0.4N)}$$

where N is the number of cluster members, R_h is the radius containing half of the cluster mass in parsecs and $< m >$ is the average mass of the cluster stars in solar unit, Spitzer & Hart (1971). In this way, the dynamical relaxation time T_R has been estimated to be 23 Myr. Thus we can conclude that NGC 2509 is dynamically relaxed and the dynamical evolution is one of the possible cause of mass segregation.

IV. CONCLUSIONS

The present study leads to the following conclusions:

(i) Using *2MASS* database, the cluster center is determined and the coordinates are found in good agreement with what obtained in *SIMBAD*. The radial density profile of NGC 2509 indicates that the extent of the cluster is 8.0 arcmin (4.6 pc), which agrees with Lyngå(1987), and the values of the core and tidal radii are found to be 0.9 and 14.0 pcs respectively.

(ii) The solar metallicity isochrone of Bonatto et al. (2004) with age of 1.6 Gyr, has been fitted to the $J \sim (J-H)$ *CMD* of NGC 2509. The distance modulus turns out to be 11.50 ± 0.10 mag, with zero reddening; corresponding to a distance of 2000 ± 85 pc. Consequently, the distances of the cluster from the galactic plane, Z, from the galactic center, R_g, and from the Sun on the galactic plane, $X_{\odot}$, $Y_{\odot}$, are found to be 203 pc; 9.7, −1.7 and 1.1 kpc respectively.

(iii) The color and magnitude ($J < 16.0$) filters cutoffs have been applied to the cluster data and its neighbor offset field. The intrinsic luminosity function of NGC 2509 is constructed by subtracting background contamination.

(iv) The luminosity function is transformed into the mass function using the solar metallicity isochrone of Bonatto et al. (2004). The *IMF* slope is found to be Γ = −2.40 ± 0.07, which agrees very well with Salpeter (1955). The total mass of NGC 2509 is found to be $\sim 800\,M_{\odot}$.

(v) Mass segregation, in the sense that massive stars tend to lie near the cluster center, is observed in NGC 2509. The dynamical relaxation time T_R has been estimated to be 23 Myr, which indicates that NGC 2509 is dynamically relaxed and mass segregation may be occurred due to dynamical evolution.

Finally, a comparisons between the results of the present work and those of Ahumada (2000) and Sujatha & Babu(2003) are given in Table 1.

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TABLE 1.
COMPARISONS BETWEEN THE PRESENT AND PREVIOUS STUDIES

Parameter	The present work	Ahumada (2000)	Sujatha & Babu (2003)
Center	$\alpha = 08^h\ 00^m\ 48^s$	$\alpha = 08^h\ 00.7^m$	$\alpha = 08^h\ 00^m\ 48^s$
	$\delta = -19^\circ\ 03'\ 06''$	$\delta = -19^\circ\ 04'$	$\delta = -19^\circ\ 03'\ 30''$
Membership	660 stars	274 stars within 3′	–
Age	1.6 Gyr.	1.0 Gyr.	8.0 Gyr.
E (B–V)	0.00 mag.	0.22 mag.	0.15 mag.
R_v	3.2	3.0	3.25
Metal abundance (Z)	0.019	0.02	–
Distance Modulus	11.50 ± 0.10 mag.	11.79 mag.	9.8 ± 0.04 mag.
Distance	2000 ± 85 pc.	2300 pc.	912 ± 15 pc.
Radius	8.0′ (4.6 pc.)	6.0′	–
Core radius	0.9 pc	–	–
Tidal radius	14 pc	–	–
Z	203 pc.	–	–
R_g	9.7 kpc.	–	–
$X_\odot$	–1.70 kpc.	–	–
$Y_\odot$	1.10 kpc.	–	–
Luminosity function	Estimated	–	–
IMF slope	– 2.40± 0.07	–	–
Total mass	≈ 800 $M_\odot$	–	–
Mass segregation	Achieved	–	–

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