

Evolution of mass segregation in open clusters: some observational evidences^{*}

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Abstract. On the basis of the best available member list and duplicity information, we have studied the radial structure of Praesepe and of the very young open cluster NGC 6231. We have found mass segregation among the cluster members and between binaries and single stars, which is explained by the greater average mass of the multiple systems. However, the degree of mass segregation for stars between 1.5 and 2.3 M_{\odot} is less pronounced in Praesepe than in the Pleiades. Furthermore, mass segregation is already present in the very young open cluster NGC 6231 although this cluster is likely still not dynamically relaxed. We discuss the implications of these results and propose a qualitative scenario for the evolution of mass segregation in open clusters.

In Praesepe the mass function of single stars and primaries appears to be significantly different, like in the Pleiades. We observe an absence of ellipticity of the outer part of Praesepe.

Key words: clusters: open – individual: Praesepe; NGC 6231 – star: formation

1. Introduction

The dynamical evolution of open clusters has been for a long time mostly a subject for models and numerical simulations. The currently accepted model predicts the appearance of mass segregation and concentration of binary stars towards the cluster centers due to equipartition of kinetic energy among cluster members, via two-body interactions (see for example the work of Spitzer & Mathieu 1980, Kroupa 1995, de la Fuente Marcos 1996, among others). As a consequence of this “standard” model, one should observe that mass segregation increases with cluster age. More precisely, if the cluster is younger than one relaxation time, it should not exhibit any mass segregation, or only marginally if the dynamical evolution is producing the segregation.

Observational evidences have so far been difficult to gather because of the generally too limited cluster surface coverage and the lack of membership criteria. Only a small number of open clusters are known to present mass segregation. A study of the

radial structure of the Pleiades, using the detailed knowledge of the membership based on proper motions, radial velocities and photometry (Raboud & Mermilliod 1998, referred to as RM98), confirms the presence of an extended corona around the cluster core and the existence of a clear mass segregation among cluster members found by van Leeuwen (1983). It also shows that the corona boundary is elliptical and that the mass function for the binary and single stars are different. Additional open clusters are known to present mass segregation: the Hyades (Perryman et al. 1997), M11, M35 and M67 (Mathieu 1983, 1984). Results are similar: the most massive and the multiple stars are always concentrated and the mass segregation is less important among the low mass stars ($M < 1 - 1.5 M_{\odot}$) in these clusters.

However very recent studies of extremely young open clusters, such as the Orion Trapezium (Hillenbrand 1997a) or embedded clusters in star-forming region (Lada & Lada 1991) have shown that massive stars are already close to the cluster center, even at ages of a million years or so. These results, unexpected within the framework of the “standard” mass segregation model, seem to imply that mass segregation in extremely young objects is unlikely the result of cluster dynamical relaxation, but may be the result of cluster formation.

To better understand open cluster dynamical evolution it seems important to examine the time evolution of mass segregation by covering a large age range. With the increasing number of observations of clusters at various ages it should be possible to produce evolutionary scenarii based on observations and provide clues for comparison with the theoretical predictions, mainly as concerns mass segregation which is directly observable. To investigate this issue we have completed extensive observational programs on three clusters with ages differing by nearly an order of magnitude: NGC 6231, the Pleiades and Praesepe (M44).

NGC 6231 (3-4 Myr) was analysed by Raboud (1996, 1997) and Raboud et al. (1997). It has been selected because of its large number of massive early-type stars and because it seems to be a fully exposed cluster with no embedded parts or links with residual nebulosity in spite of its young age. It is therefore a very good example of a very young cluster, probably not much influenced by stellar or dynamical evolution.

The Pleiades have been analysed in a previous paper (RM98) and a fine mass segregation has been clearly established. Al-

^{*} Tables 2 and 3 are available only in electronic form from the Strasbourg ftp server at 130.79.128.5

though the Pleiades do not present red giant stars as some clusters of the same age do, their properties seem representative of the characteristics of similar open clusters, e.g. NGC 2422. However the proximity of the cluster and the large proper motion make it possible to safely identify cluster members in the outer parts.

Results to be published (Mermilliod & Mayor 1998) are used to study the structure of Praesepe with an approach similar to that used for the investigation of the Pleiades. The reason to select Praesepe is again its proximity, the large proper motion and the extensive radial-velocity material obtained over 20 years of observations which helps defining the membership and identifying the binary stars.

We first present the available data for Praesepe and NGC 6231 in Sect. 2. We analyse the structure of the two clusters in Sect. 3. In Sect. 4 we discuss the comparison between the structures of NGC 6231, the Pleiades and Praesepe. Section 5 summarizes the main results and concludes the paper.

2. Observational data

2.1. Praesepe

2.1.1. Sample

The complete list of members used in the investigation includes not only the central part considered by Klein-Wassink (1927, referred to as KW), but also a wide surrounding area, out to 4° from the center investigated by Mermilliod et al. (1990) who identified 43 corona members. The membership attribution is based on proper motion, radial velocity and photometry. The discussion of the membership and binarity of about 100 (F5-K0) stars in Klein-Wassink (1927) area is in preparation (Mermilliod & Mayor 1998). The binary status has been examined and 25 spectroscopic binaries have been discovered. Three of them are found in triple systems (Mermilliod et al. 1994). Eighteen orbits with periods between 3.9 and 7400 days have been determined.

These two lists form the most complete sample of members earlier than K0 out to 4° from the cluster center. We cannot claim that all corona members have been discovered, because the proper motion surveys (Artjukhina 1966a, 1966b) are of medium precision. However, the 43 corona members already represent 51% of the total number of F5-K0 members. Any new F5-K0 member added to the halo sample will enhance the observed mass segregation.

2.1.2. Binarity among the upper main sequence

The radial-velocity observations for stars on the upper main sequence (MS) are rather old and partly unpublished. The available information is mostly based on the radial velocities published by Wilson & Joy (1950), two or three spectra per star obtained around 1923. The individual measurements have been published in Abt's (1970) compilation of Mt-Wilson observations. Rebeiro (1966) has published mean values based on the objective prism technique. The results of McDonald (1959) and Trumpler have not been published, but a copy of the mean values

had been kindly communicated by Hill (1978). Radial velocities (one or two per star) have been obtained by Dickens et al. (1968), but the Julian dates have not been published.

Table 1 summarizes the available information. It gives the KW identification, the results of Wilson & Joy (1950), mean radial velocities, standard errors and number of measurements, those of McDonald (1959) and Trumpler, mean radial velocities and number of spectra, and of Rebeiro (1966), mean radial velocities, errors and number of plates. The remarks comment on the binary status. They have been deduced from the notes of each study and from the comparison of the mean radial velocities obtained at different epochs.

We have also observed several Am stars with the CORAVEL scanner and got an orbit for three of them, KW 40, 279 and 538. The orbit for the double-lined Am binary KW 229 (Sanford 1931) has been known for many years. Our observations confirm his elements. KW 40 is another triple system in Praesepe, with a short period of 6 days, and a long one around 2900 days. The discussion of these orbits will be presented in another paper.

Multiplicity of the red giants has been discussed by Mermilliod & Mayor (1989): KW 428 is a binary with a period of 998 days.

2.1.3. The member catalogue

Table 2 summarizes the available data for our working list of 185 Praesepe members. It contains the star identification, V and $B - V$ from BDA, the open cluster database (Mermilliod 1995), the x and y rectangular positions in arc minutes, the distance from the cluster center, the multiplicity status, remarks and the deduced masses of the stars and components. Table 2 is available only in electronic form from the Strasbourg anonymous ftp server (130.79.128.5). For single stars the individual masses have been determined from the B-V colour index with a power law relation between mass and B-V derived from an isochrone computed from the models of Schaller et al. (1992) for $\log t = 8.92$ and $z = 0.02$. For the binary stars presenting a marked displacement above the ZAMS in the colour-magnitude diagram, we have proceeded as explained in a similar discussion of the Pleiades (RM98).

2.2. NGC 6231

2.2.1. Sample

NGC 6231 is one of the richest and youngest exposed open cluster known (Mermilliod 1981; Meynet et al. 1993). It is located at $l=343^\circ 5$ and $b=1^\circ 2$. This cluster is found near the southern end of the very young association Sco OB1 and is usually considered as its nucleus (Perry et al. 1991).

However, the amount of data concerning NGC 6231 is beyond comparison with those available for Praesepe or the Pleiades, mainly because of its larger distance (1.8 kpc, Raboud et al. 1997), although efforts have been done to improve the data. Raboud (1996) investigated the binarity among B-type stars from ESO 3.6m radial velocities. He derived a minimum bi-

Table 1. Literature data for upper MS members in Praesepe.

KW	Wilson	σ	n	McD	n	Tr	n	Reb	σ	n	Remarks ¹
38	34.1	7.2	3			32.1	3	31.	2.0	7	
40	34.4	5.3	3								SB1O
45	31.0	0.6	3	33.9	3	32.2	4	29.	7.5	7	
50	27.4	1.7	4	34.2	4	34.7	5	33.	7.5	4	
114	34.8	4.3	3	29.0	3	32.1	4	36.	7.5	7	
124				21.7	1	30.0	3	20.	3.5	7	SB1O
143	28.4	3.8	3	27.5	1	32.4	4	36.	3.5	7	
150	30.9	10.2	3	32.7	4	30.8	3	26.	7.5	6	SB1
203	36.5	7.4	3	36.8	1	29.6	4	42.	7.5	7	VB, 0 ^h .4
204	30.6	3.5	4	33.4	3	27.6	4	37.	7.5	2	
207	30.7	9.7	3	35.3	2	34.6	4	24.	7.5	7	SB1
218						27.6	4	35.	3.5	7	
226						39.0	5	31.	2.0	7	
229				36.3	2	31.7	3	26.	3.5	5	SB2O
265	33.1	3.0	3	35.4	2	32.6	3				OccB, 0 ^h .4
271						38.6	5	37.	2.0	2	PHB
276	38.5	4.8	4	27.1	3	31.1	4	39.	2.0	6	SB1
279	16.3	14.1	3	19.2	2			22.	2.0	2	SB1O
284	30.7	2.9	4	28.7	3	39.9	5	42.		1	OccB, 0 ^h .11
286	27.3	1.0	3			38.4	5	28.	3.5	7	
292	-22.0	94.6	2					26.	3.5	7	SB2
295						34.4	3				
300	20.7	27.3	8	59.3	1	38.2	2				SB2
318						39.7	3	5.	3.5	7	
323	37.1	5.9	3	34.8	1	32.8	3	34.	2.0	7	PHB
328	36.8	2.8	3	21.4	1	35.5	3	2.		1	SB2
340						31.7	4	31.	2.0	7	
348	27.6	5.5	6	38.5	3	30.3	4	19.		1	
350						33.0	3	29.	3.5	7	
370						32.5	3	33.	3.5	7	
375	33.2	8.2	2			29.5	5	34.	3.5	7	SB1
385	40.8	20.8	3					34.	3.5	7	VB, 2 ^h .1
411								29.	7.5	7	
429								29.	7.5	7	
445	27.1	1.3	2	36.1	3	36.8	3	33.	7.5	7	
449				24.0	2	36.6	3				
459						31.2	4	23.	3.5	7	

¹ spectroscopic binary: SB1, SB2, with orbit: SBO;
 photometric binary: PHB; visual binary: VB;
 occultation binary: OccB

nary fraction of 52 % in the considered population. Raboud et al. (1997), using Geneva photometry, identified 64 new members out to a distance of 13' from the center, extending the Seggewiss area (8'). References to previous works on NGC 6231 can be found in these two papers.

As a consequence of the small amount of available data, we concentrate on the existence of mass segregation in this very young open cluster.

2.2.2. The member catalogue

We have composed a large table collecting all 300 members brighter than $V_0 = 12.5$ from Raboud et al.'s (1997) catalogue,

completed with *UBV* (Seggewiss 1968, Garrison & Schild 1979) and *wby* (Balona & Laney 1995) photometric data. 192 stars are measured in the Geneva system, 66 in *UBV* and 42 in *wby*. Table 3 contains the star identification, V and $(B - V)$, $[B - V]$ or $b - y$ depending on the photometry used, the photometric system used, the x and y rectangular positions in arc minutes, the distance from the cluster center, the multiplicity status, remarks and the deduced masses of the stars and components. Table 3 is available only in electronic form from the Strasbourg anonymous ftp server (130.79.128.5).

The individual masses of the stars have been derived by different techniques depending on the photometry used and on the multiplicity status. For stars measured in the Geneva system, we derived the temperature with the calibration of the X parameter (Cramer 1984). The mass is then obtained with an isochrone calculated by the models of Schaller et al. (1992) for $\log t = 6.6$ and $z = 0.02$. This method is only valid for the hotter stars. However, for temperatures greater than $\log T_{\text{eff}} = 4.5$ the relation between the mass and the temperature becomes too vertical and the mass determination failed. In these cases we only considered a lower mass limit of $22 M_{\odot}$ for the stars.

For stars outside the calibration range of the X parameter, we used the relation between $[B - V]_0$ and the mass derived from the same isochrone. A similar technique is used for stars measured in *UBV*. For the *wby* data we compute the temperature from $(b - y)_0$, with the calibration of Hauck & Künzli (1996). The mass is derived with the isochrone defined above.

All these techniques are valid *only* if the stars are on the main sequence. Raboud et al. (1997) showed the existence of a candidate pre-main sequence (PMS) population. The mass of the stars belonging to this population have been estimated with the PMS evolutive tracks from Bernasconi (1996).

The derivation of the multiple star components make use of similar techniques as the ones described in RM98.

3. Structure

3.1. Praesepe

This section presents a study in every respect similar to that described in RM98 for the Pleiades, to facilitate comparisons. Therefore we give here only the results with a minimum of details. The reader is referred to RM98 for the explanations of the various methods and formulae used, and for precise definitions.

3.1.1. Global overview

From the data collected in Table 2, we have computed the cluster mass center: $\alpha_{1950} = 8^h 37^m 32^s$; $\delta_{1950} = 19^{\circ} 48' 8''$ and used it to plot a chart of the Praesepe cluster (Fig. 1) displaying the single stars as filled circles and the multiple ones as open circles.

The cluster appears circular out to 3° from its center. In order to compare the overall shape of Praesepe with that of the Pleiades (RM98) we divided the two clusters in several sectors

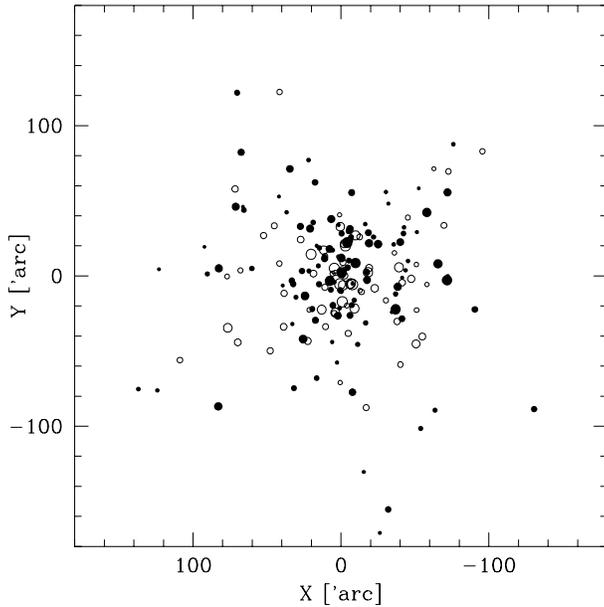


Fig. 1. Map of Praesepe displaying all the member stars considered in this study. Open circles are multiple stars and filled circles stand for single stars. The point sizes are related to the magnitudes of the stars or systems. North is at the top and East at the left of the map.

Table 4. Comparison between the asymmetry estimators for Praesepe and the Pleiades.

Cluster	$p=8$	$p=12$
Praesepe	0.124	0.135
Pleiades	0.215	0.207

and computed an *asymmetry estimator* (Bouvier 1961) defined as

$$D = \frac{1}{N} \sum_{i=1}^p |n_i - \bar{n}|, \quad (1)$$

where N is the total star number, p is the number of sectors, n_i is the number of stars in the i th sector and $\bar{n} = N/p$. D varies in the interval $[0,2]$, with $D=0$ corresponding to a circular cluster and $D \rightarrow 2$ corresponding to a linear arrangement of the “cluster” stars.

Table 4 displays the asymmetry-estimator values for two cluster subdivisions (8 and 12 sectors, respectively). In both cases, Praesepe appears clearly more circular than the Pleiades. Therefore the known halo of Praesepe do not present any ellipticity such as that observed for the Pleiades (RM98).

Following Wielen (1975), the ratios of the three orthogonal axes of a cluster, considered as a tridimensional ellipsoid, should be 2.0:1.4:1.0. The larger axis is pointing towards the galactic center and the smaller one is perpendicular to the galactic disk. As Praesepe lies at a galactic longitude of $205^\circ 5$ and is close to us (158 pc), we only observe the ratio of the second and third axes, namely 1.4:1.0, which corresponds to an ellipticity of 0.29. However, Praesepe is ~ 85 pc above the galactic plane and we

see it under an angle of $32^\circ 5$. We thus observe an effective axial ratio of 1.02:1.0, which corresponds to an ellipticity of only 0.02. This theoretical expectation agrees with our observation of a projected round-shaped halo for Praesepe.

However, the absence of ellipticity of the outer part of Praesepe could also be real and not an artifact of projection effects. If real, the round-shaped halo may be the signature of multiple interactions between the cluster and interstellar clouds, because such gravitational interactions rapidly stripped off the outermost halo stars, which filled the elliptical region allowed by the galactic tidal field. This scenario (Wielen 1974) predicts that the oldest clusters should have the more circular halos, because they have statistically suffered more encounters with interstellar clouds than younger clusters.

Nowadays, Praesepe is the oldest open cluster for which we have a characterisation of its halo shape, which is consistent with the theoretical expected ellipticity. The Pleiades (RM98), NGC 3532 (Gieseking 1981) are younger, the Hyades (Oort 1979) have the same age, and they all present elliptical outerparts. Therefore it would be very interesting to investigate whether clusters older than Praesepe have elliptical halos or not. Such investigations would constrain the frequency of gravitational encounters between open clusters and interstellar clouds.

3.1.2. Mass segregation

The concentration of multiple stars relative to single ones, of bright stars relative to fainter ones, and of massive stars relative to less massive ones is apparent in Figs 2 and 3. These two figures represent the radial extension of stars of different magnitudes or masses and also show the completeness status of our survey in terms of magnitude, mass and radial extensions. Fig. 3 very clearly demonstrates that the size of the cluster increases when the mean stellar mass decreases. The trend is surprisingly rather well defined. As a consequence the definition of cluster radii is not simple and visual estimates of this parameter on photographs is very subjective and prone to large errors depending on the density of the stellar background on which the cluster is projected. There is only one star more massive than $2 M_\odot$ out of the limit defined by the trend (lying out to 2° from the center). Although in principle stars of any mass could be found anywhere inside the cluster boundaries, it appears that energy equipartition confines the stars in bounded volumes. Are the stars observed outside the normal boundaries being ejected and leaving the cluster, although they are still located within the tidal radius ?

To investigate more accurately the radial distribution of the different star populations we have split the sample into classes, according to the stellar multiplicities and to the stellar masses.

Single and multiple stars: The multiple systems are clearly more concentrated towards the cluster center than the single stars (Fig. 4). A Kolmogorov-Smirnov test indicates that the probability of false rejection of the null hypothesis, i.e. that the two distributions are identicals, is 9.4 %.

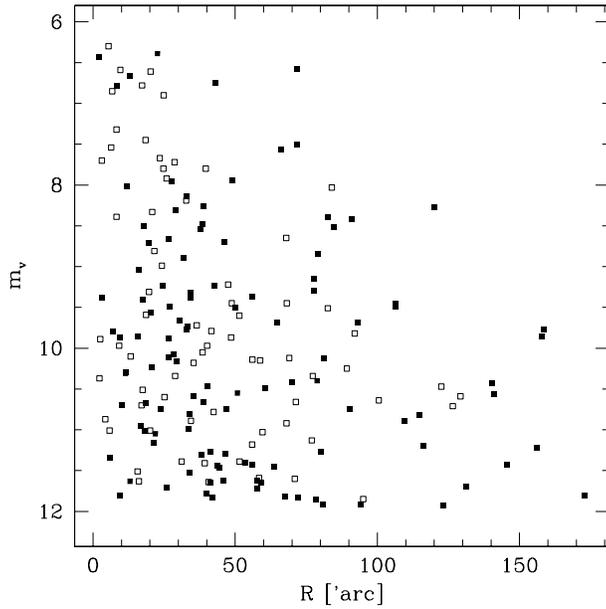


Fig. 2. Apparent magnitudes of the stars as a function of their radial distances to Praesepe center. The open and filled squares denote multiple and single stars respectively.

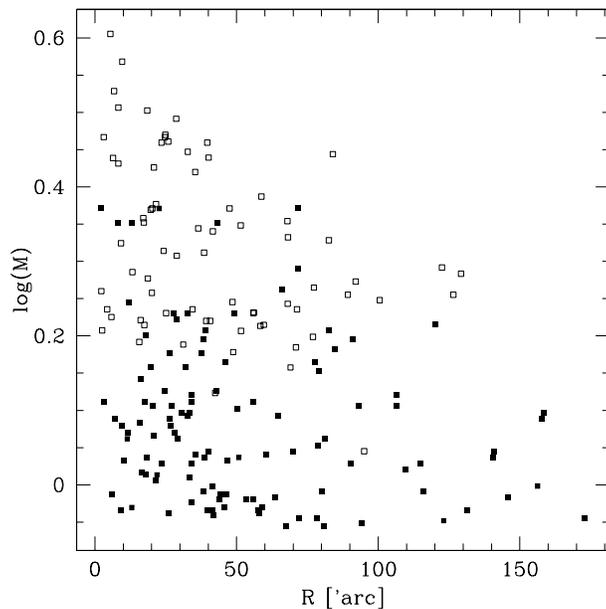


Fig. 3. Logarithm of the star masses as a function of their radial distances to Praesepe center. This diagram is a direct representation of mass segregation. Same symbols as in Fig. 2.

Among the multiple star population itself we can divide the sample between “short period” binaries (spectroscopic) and “long period” binaries (visual, occultation and photometric binaries). The resulting two cumulative distributions are plotted in Fig. 5. Their radial distributions are very similar.

These results agree with the hypothesis that the radial segregation of binaries towards the cluster center depends mainly on the total mass of the systems, and not on their periods (at least for periods smaller than $\sim 10^3$ yr). The same conclusion

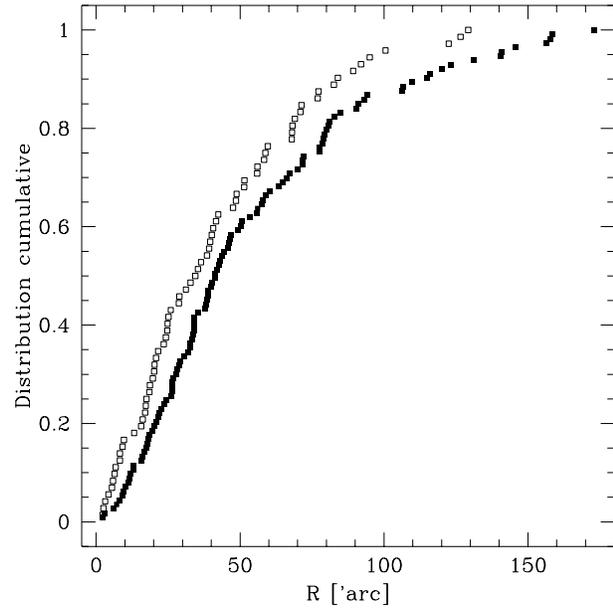


Fig. 4. Cumulative distributions for the multiple stars (open squares) and the single stars (filled squares) in Praesepe.

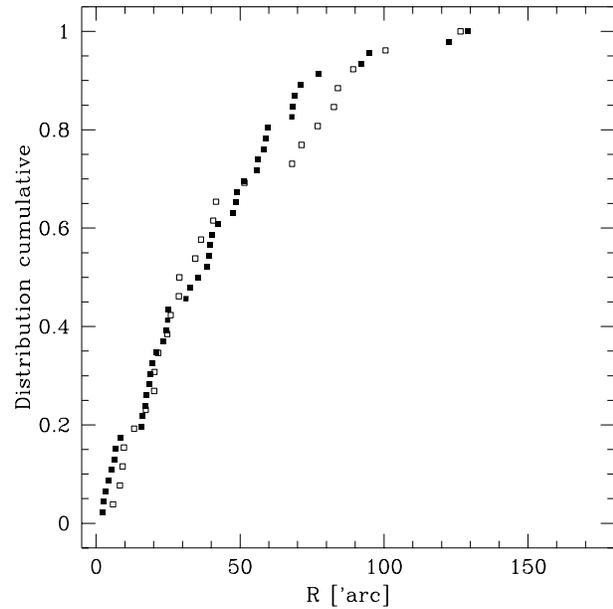


Fig. 5. Cumulative distributions for the “short period” binaries (filled squares) and the “long period” binaries (open squares) in Praesepe. See text for more details.

was obtained and discussed by Raboud & Mermilliod (1994) and by RM98 in the Pleiades.

Sample subdivision using mass criteria: To characterize the degree of mass segregation among different populations in the cluster, we subdivide the sample into 4 groups. Fig. 6 represents the cumulative distributions for 4 mass intervals, chosen identical as those used in the study of the Pleiades (RM98).

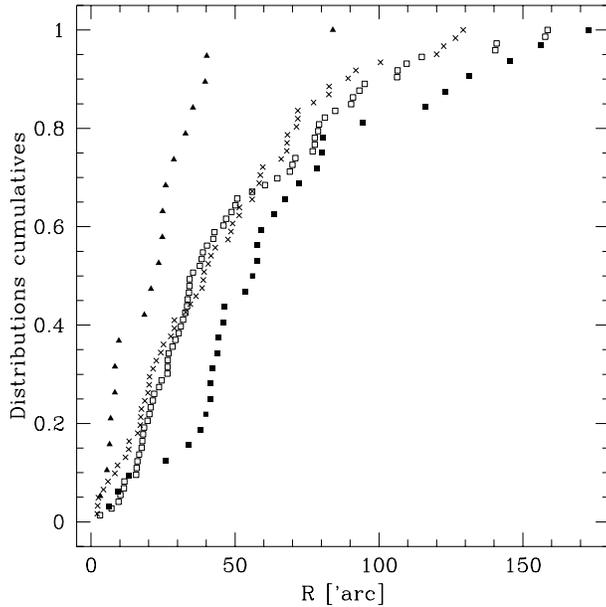


Fig. 6. Cumulative distribution functions for different mass intervals in Praesepe: $M < 1 M_{\odot}$ (filled squares), $1 < M < 1.6 M_{\odot}$ (open squares), $1.6 < M < 2.5 M_{\odot}$ (crosses) and $M > 2.5 M_{\odot}$ (filled triangles).

Table 5. Characteristic radii [$'$] for different member sub-samples in Praesepe. The errors associated with $r_{n/2}$ and $r_{m/2}$ are typically between 3 and 7 [$'$].

Population	$r_{n/2}$	$r_{m/2}$	r_c	r_t	\bar{r}
Complete sample	39	34	22 (10)	242 (107)	65 (13)
Bright stars	28	25	16 (14)	227 (346)	47 (19)
Faint stars	42	41	25 (16)	271 (205)	73 (20)
Massive stars	33	29	17 (13)	248 (312)	53 (17)
Less massive stars	43	42	27 (18)	270 (224)	74 (22)
Single stars	41	40	24 (15)	271 (199)	71 (19)
Multiple stars	34	28	19 (17)	238 (350)	53 (19)

The most massive stars in Praesepe are obviously more concentrated than stars of smaller mass, while the stars with masses less than $1.0 M_{\odot}$ are the least concentrated. The important and new point is the similarity between the radial distributions of the two intermediate mass intervals. In this mass interval ($1.0 < M < 2.5 M_{\odot}$) we find the surprising result that the degree of mass segregation is less pronounced in Praesepe than in the Pleiades, in spite of the greater age of the former cluster.

3.1.3. Characteristic radii

We derived the values of the radius containing half of the total number of stars ($r_{n/2}$), the radius containing half of the total mass of the stars ($r_{m/2}$), the core (r_c), the tidal (r_t) and the harmonic radii (\bar{r}). These derivations were done for different member sub-samples, following the procedures described in RM98. The results are presented in Table 5, with their uncertainties indicated in brackets.

Table 6. Values of different power law exponents ($1 + x$) in Praesepe. The cluster inner part is the central 2-pc disk, and the cluster outer part is outside this disk.

Sample	($1 + x$)
(1) Complete sample (with unresolved binaries)	2.3 ± 0.4
(2) Complete sample (singles + primaries)	2.5 ± 0.3
(3) Singles	2.8 ± 0.3
(4) Primaries	2.1 ± 0.3
(5) Cluster inner part (singles + primaries)	1.6 ± 0.4
(6) Cluster outer part (singles + primaries)	3.6 ± 0.7
(7) Complete sample (mass summed)	1.2 ± 0.2
(8) Cluster inner part (mass summed)	0.6 ± 0.1

We adopt cut-off values similar to those used for the Pleiades (RM98), namely $V=9.6$ and $M=1.5 M_{\odot}$, to subdivide the bright/faint and the massive/less massive stars respectively.

The various parameters describing Praesepe are (for a distance of 158 pc): $r_c = 1 \pm 0.5$ pc, $r_t = 11.1 \pm 5$ pc, $r_{n/2} = 1.8 \pm 0.2$ pc, $r_{m/2} = 1.6 \pm 0.2$ pc and $\bar{r} = 3 \pm 0.6$ pc.

3.1.4. The mass functions

Due to the improved material collected in this paper, we are able to compute various mass functions for Praesepe. This will allow us to test the effect of unresolved binaries, of the radial extension of the survey and to confirm whether the mass function for single stars is different from the mass function of the primaries of multiple systems, as it was observed in the Pleiades (RM98).

We fitted a Salpeter-type power law in the form

$$\log \left(\frac{df}{dM} \right) = C - (1 + x) \log(M) \quad (2)$$

throughout the observed data. In Eq. (2) df/dM is the number of stars per unit mass as a function of mass M . C is a constant and $(1 + x)$ is the power law exponent, which has the value of 2.35 following Salpeter (1955).

The slope derived without any correction for the binary content has a value of 2.3 ± 0.4 (case 1 in Table 6), which agrees with the Salpeter one.

The slope derived for the single stars and the primaries of multiples systems, using the available information about them, is 2.5 ± 0.3 (case 2 in Table 6). This value is in agreement with the previous one and confirms the result obtained in the Pleiades (RM98): the determination of the mass-function slope is not seriously affected by unresolved multiple stars.

We are also able to compare the mass function of single stars (case 3 in Table 6) and of primaries of multiple systems (case 4 in Table 6). We observe that the slope of the single star mass function is steeper than that for the primaries (Fig. 7). This result implies that the components of binary systems are not drawn independently from the same mass function as that of single stars. This was already reported for the Pleiades (RM98) and was qualitatively explained by dynamical evolutionary effects. Praesepe, older than the Pleiades, has probably undergone a

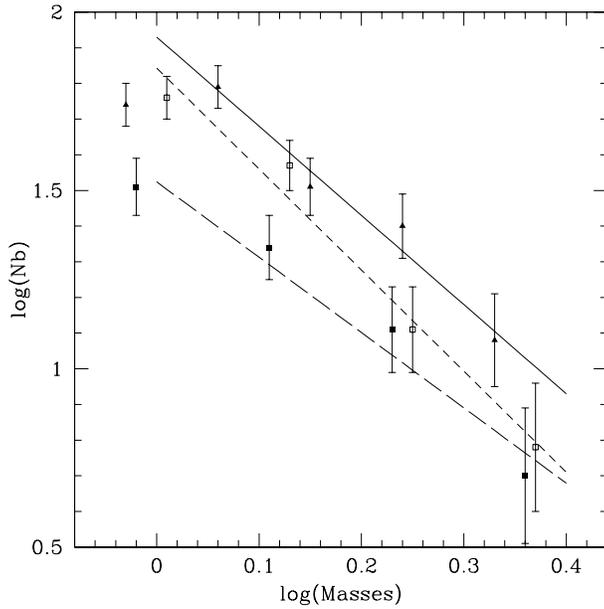


Fig. 7. Mass functions in Praesepe. The solid line stands for the complete sample (single stars and primaries). The long-dashed line represents the mass function of the primaries and the short-dashed line stands for the single stars.

more complete dynamical evolution and the encounters between single stars and binaries, leading to the capture of the more massive stars into the multiple systems (Mathieu 1985), have had time to flatten the primary mass function.

3.1.5. The frequency of multiples star systems

Our direct detections of multiple systems give a proportion of 43% of binaries in the central 2-pc disk and of 34% in the outer part of the cluster. The difference between the inner and outer parts is less pronounced than that observed for the Pleiades (RM98), i.e. 48% in the central 2-pc disk, 20% outside, although Praesepe overall binary fraction (39%) is larger than that of the Pleiades (32%).

It is interesting to compare these results with the work of Kroupa & Tout (1992). Their analysis of the photometric colour-magnitude diagram in Praesepe yielded a large binary frequency. Values close to unity would be still acceptable although smaller fractions could not be excluded.

3.1.6. Estimation of the cluster total mass

We have shown (RM98) that the estimation of the cluster total mass is a very difficult task producing results with large uncertainties. We derive values between 157 and 3970 M_{\odot} for the total mass of Praesepe (Table 7). These results were obtained using either the integration of the cluster mass function, including the contribution of binary companions, or the relation between the tidal radius and the cluster mass (King 1962):

$$M_c = \frac{4A(A-B)}{G} r_t^3 \quad (3)$$

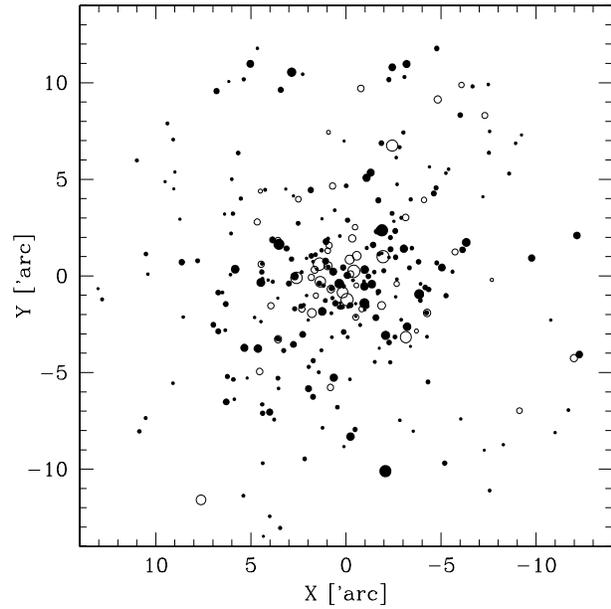


Fig. 8. Map of NGC 6231 displaying all the member stars considered in this study. Open circles are multiple stars and filled circles stand for single stars. The point sizes are related to the magnitudes of the stars or systems. North is at the top and East at the left of the map.

where G is the gravitational constant, r_t is the tidal radius of the cluster, A and B are Oort's constants of galactic rotation. The tidal radius considered in Eq. (3) is measured in the direction of the galactic center. However, we only observe the tidal radius perpendicular to this direction but parallel to the galactic disk. In Sect. 3.1.1 we found that Praesepe may have a flattening close to the theoretical expected one. We could therefore consider that we have a cluster with axes ratios 2:1.4:1 and then the tidal radius in the direction of the galactic center has a value of $2/1.4$ times the value of the observed tidal radius ($242'$ from Table 5). Finally, if we sum up all the stellar masses derived for our whole sample of stars, which is the only way to properly compute the cluster mass, we obtain $300 M_{\odot}$.

3.2. NGC 6231

3.2.1. Completeness of the member list

From the data collected in Table 3, we have computed the cluster mass center and we considered star S320 (Seggewiss 1968) as lying at the center: $\alpha_{1950} = 16^h 50^m 41^s$; $\delta_{1950} = -41^{\circ} 44.9'$. Fig. 8 shows a chart of NGC 6231 displaying all the member stars considered in the present study. The filled and open circles represent single and multiple stars respectively. The size of the circles is proportional to the star magnitude.

Figure 9 displays the increase of the cluster size with the decrease of the star luminosity, which is equivalent to a decrease of mean stellar masses. Although the exact radius at any mass is somewhat fuzzy, probably because of the presence in the sample of a few stars belonging to the association surrounding NGC 6231, mass segregation is clearly present in this diagram.

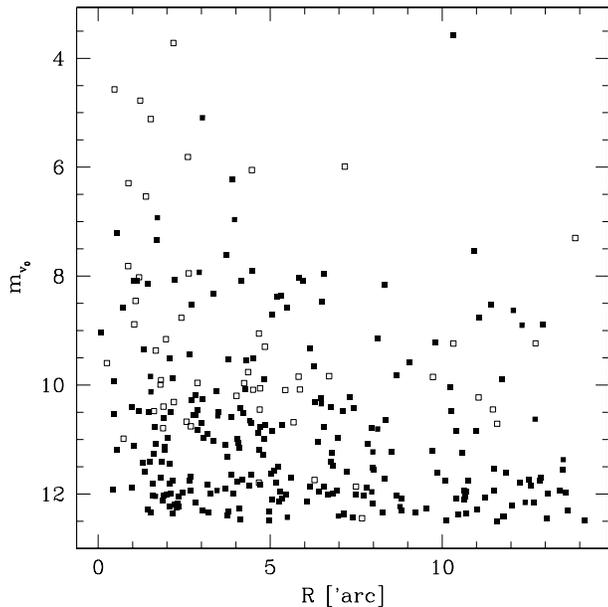


Fig. 9. Apparent magnitudes of the stars as a function of their radial distances to the center of NGC 6231. The open and filled squares denote multiple and single stars respectively.

Table 7. Results of the different Praesepe total mass determinations (see text for more details).

Method	Cluster total mass	1σ confidence interval
	M_{\odot}	M_{\odot}
Tidal radius (with correction for the cluster flatness)	1330	[229, 3970]
Tidal radius (without correction for the cluster flatness)	440	[157, 987]
Mass function	590	[416, 900]
Summed mass	300	

The massive stars ($V < 7$) occupy a much smaller volume than the less massive stars ($V > 10$). It will be more quantitatively characterized in the next section.

The status of the outlying stars, i.e. those stars found at larger distance from the cluster center than the bulk of stars at the same magnitude is worth considering. In particular the membership of the nine bright stars (Nos 501, 723, 724 726, 745, 749 769, 774 and 810) of the cluster corona (i.e. the region between ~ 8.5 and ~ 13.5 [arc]) has been discussed in Raboud (1997). These stars, considered as cluster members from the photometric analysis, are probably member of the Sco OB1 association. An estimate of the stellar contamination due to the association was done using the Guide Star Catalogue (GSC), for stars brighter than $V=11.4$ (corresponding to the fainter reddened magnitude of the 9 discussed stars). It results that the bright stars of the cluster corona have a probability of more than 50% of belonging to the association rather than to NGC 6231. In the following discussion we shall consider both cases, with and without these stars.

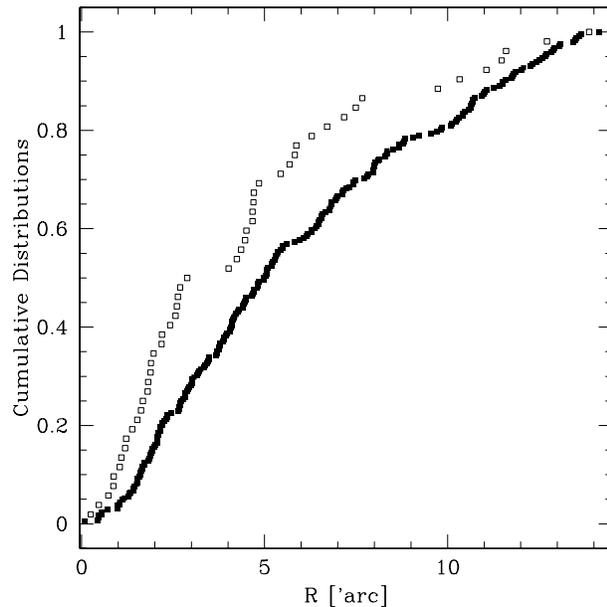


Fig. 10. Cumulative distributions for all the multiple stars (open squares) and the single stars (filled squares) in NGC 6231.

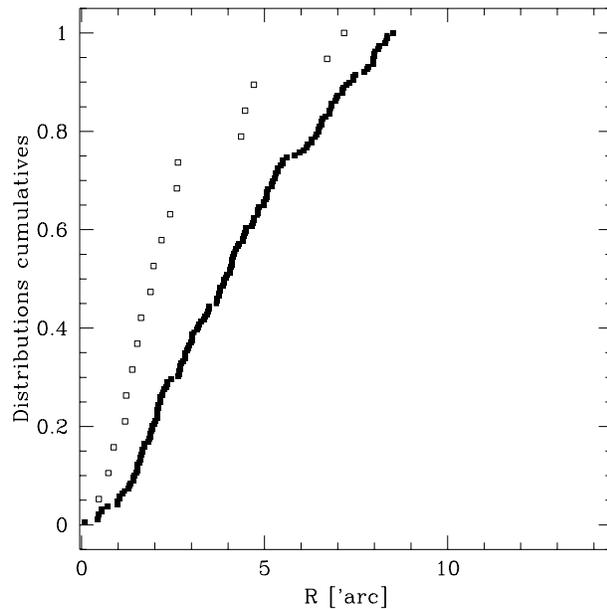


Fig. 11. Cumulative distributions for the multiple stars, spectroscopically detected, (open squares) and the single stars (filled squares) in NGC 6231.

3.2.2. Mass segregation

Single and multiple stars: Fig. 10 shows the cumulative distributions for the multiple stars (open squares) and the single stars (filled squares). The multiplicity status was derived from radial velocity studies (Levato & Morrell 1983; Perry et al. 1990; Raboud 1996) and photometric criteria. Because of the low efficiency of photometric criteria on the steep upper main sequence, Fig. 11 presents the distributions of only spectroscopic multiple stars and single ones in the cluster central $8'$, where spectro-

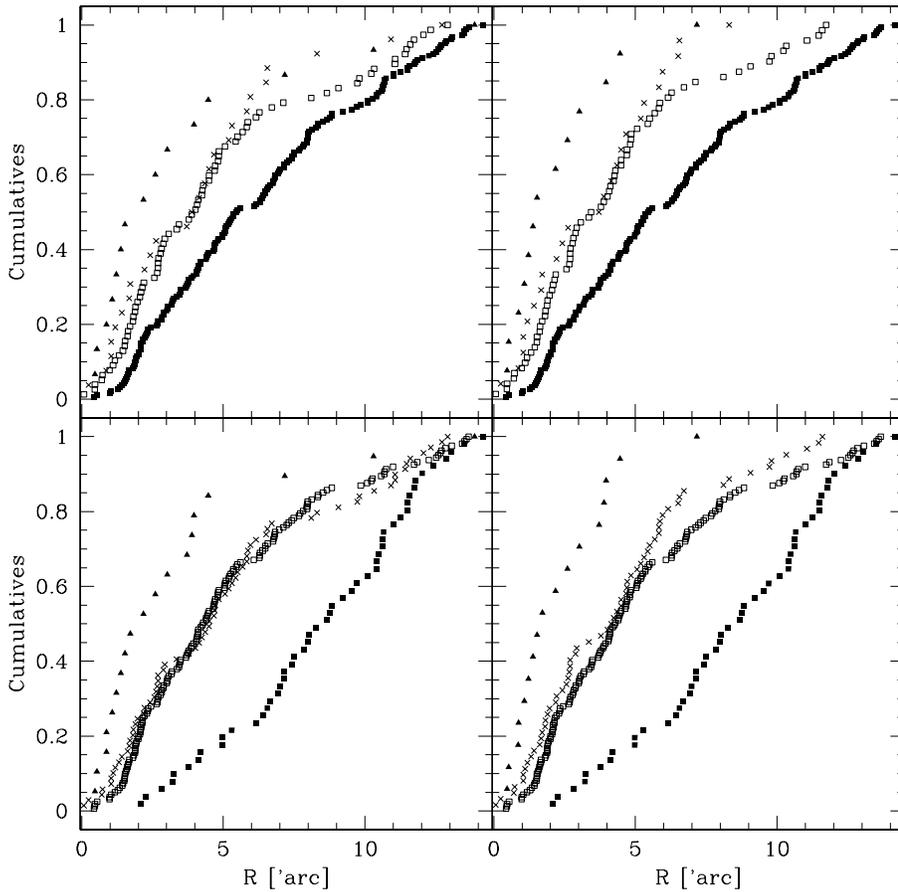


Fig. 12. Cumulative distributions for two mass interval sets in NGC 6231. For the two top figures: $M < 5 M_{\odot}$ (filled squares); $5 \leq M < 10 M_{\odot}$ (open squares); $10 \leq M < 20 M_{\odot}$ (crosses) et $M \geq 20 M_{\odot}$ (triangles). For the two bottom figures: $M < 2.5 M_{\odot}$ (filled squares); $2.5 \leq M < 6.3 M_{\odot}$ (open squares); $6.3 \leq M < 15.8 M_{\odot}$ (crosses) et $M \geq 15.8 M_{\odot}$ (triangles). The figures at the left contain all the sample stars. The figures at the right do not include the 9 bright stars of the cluster corona (see Sect. 3.2.1).

scopic information is available. NGC 6231 presents the unique feature that 8 among the 10 brighter stars are spectroscopic binaries with periods shorter than 6 days (Hill et al. 1974; Levato & Morrell 1983)

In both Figs. (10 and 11) the multiple stars appear to be more concentrated than the single ones. Kolmogorov-Smirnov tests clearly confirm that the two distributions are different. For Fig. 10 and 11 respectively: the probabilities are of 0.2 % and 1.2 % to reject the null hypothesis, that the two distributions are the same, even though it is true.

Sample subdivision using mass criteria: The four diagrams of Fig. 12 clearly indicate the existence of mass segregation in NGC 6231. In the top two diagrams of Fig. 12 the mass intervals are set differently from those in the bottom two panels. The two left hand diagrams of the same figure include the 9 bright stars of the cluster corona, while the right hand two diagrams do not (see the caption of Fig. 12 for interval limits).

Mass segregation is more pronounced for the massive stars (triangles), while stars with masses in the range $5 \leq M < 20 M_{\odot}$ are spatially well mixed (open squares and crosses). This latter population is however more concentrated than the lower-mass population (filled squares).

From these curves, we conclude that only a dozen, bright, massive, mainly binary stars are well concentrated toward the cluster center. The intermediate mass stars ($5 < M < 20 M_{\odot}$) are

more uniformly distributed over the cluster area, which means that mass segregation is not yet established over a rather large mass interval.

4. Discussion

Our main goal, as stated in the Introduction, is to use these new results to test the usual explanation of mass segregation in term of dynamical relaxation over a large age interval. We then need to compare the radial structure of the three open clusters (NGC 6231, Pleiades and Praesepe) and the observed mass segregation. We shall also consider published results for a few other clusters (MonR2, Orion, M11, M67).

4.1. Relaxed clusters: Pleiades and Praesepe

Both clusters, respectively 10^8 and 8×10^8 yr old, should be well relaxed (the typical relaxation times for these open clusters are estimated at around 10^7 yr). As a consequence of equipartition of kinetic energy between stars of different mass, both clusters should exhibit similar mass segregation. We observe that this effect is alike for the most massive stars, but appears less pronounced in Praesepe than in the Pleiades for the intermediate mass stars, although M44 is about 8 times older than the Pleiades (Fig. 14a–c).

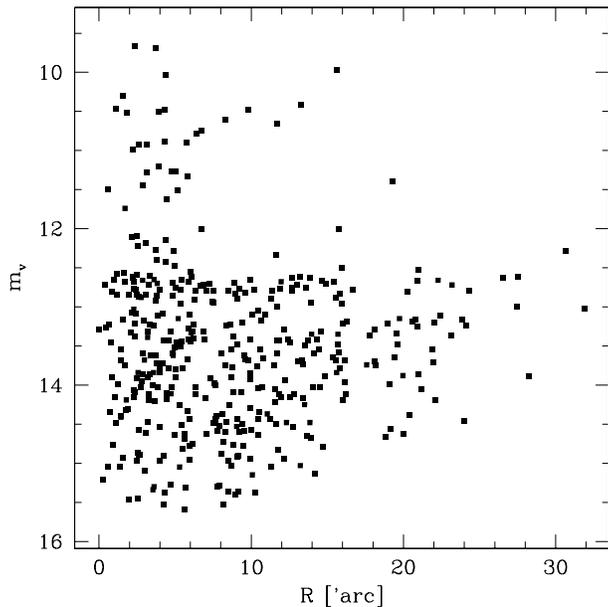


Fig. 13. Apparent magnitudes of the stars as a function of their radial distances to the center of M67. The HEP (Hydrogen Exhaustion Phase) gap is apparent at $V \sim 13$. This radial distribution of stars contrasts dramatically with those presented for NGC 6231 and Praesepe (figs. 9 and 2).

Mathieu (1984) has examined the structure and mass segregation in NGC 6705 (M11) on the basis of extensive proper motions and photometry. This cluster has an age intermediate between that of the Pleiades and Praesepe ($\sim 2.3 \times 10^8$ yr), with the mass of the most massive stars around $3.5 M_{\odot}$. His Fig. 9 offers a clear evidence for a fine mass segregation and is very similar to our Fig. 14b (Pleiades).

The old open cluster M67 behaves quite differently: the radial distribution of the member stars (Fig. 13) contrasts dramatically with those presented for our three clusters. It presents a small amount of mass segregation for single stars with $M \sim 1.5 M_{\odot}$. Only red giants, blue stragglers and binaries are somewhat concentrated towards the cluster center (Mathieu 1985). Fig. 13 also reveals the incompleteness of the membership list in the outer part resulting either from the lower completeness of measurements of fainter stars at large distance from the cluster center or from the membership estimates.

We will now consider two possible explanations for the less pronounced mass segregation observed in Praesepe.

4.1.1. The dominant mass component

The first one follows the results of numerical simulations by Spitzer & Shull (1975). From them we infer that if stars belonging to a small range of mass constitute almost all the cluster mass, the spatial distribution of that component will be unaffected by interactions with stars of other mass groups. Accordingly one should observe little, if any, mass segregation among this dominant group. The other stars will be either more or less concentrated, on whether they are heavier or lighter than the

dominant group. This kind of mass segregation will be only slightly dependent on the exact individual stellar masses.

In the case of Praesepe, we note that the total cluster mass *effectively* observed (derived by summing up all the stellar masses) is contained within the interval of the theoretically estimated masses (Table 7). It was not the case for the Pleiades (RM98). We then observe a large part of the total mass of Praesepe. If we consider that stars with masses between 0.9 and $2.3 M_{\odot}$ constitute the dominant mass group of the cluster, we should observe little, or no, mass segregation among this group. Furthermore, all heavier stars ($M > 2.3 M_{\odot}$) should be identically more concentrated. This description would explain correctly our results.

4.1.2. The potential well

The second explanation could be related to the smaller total mass of Praesepe (Sect. 3.1.6), compared to that of the Pleiades (RM98). Praesepe has then a shallower potential well than the Pleiades and the velocity distribution of the stars of Praesepe are more severely truncated by the galactic tidal field (the two clusters have similar galactic locations). This will result in a lesser degree of mass segregation among Praesepe stars (Mathieu 1985).

However, we should keep in mind that the comparison between Praesepe and the Pleiades has a limited validity, because the two clusters could have experienced different external constraints. For instance, we could not exclude that the lesser degree of mass segregation observed in Praesepe may be due to the effects of external forces acting on the cluster.

4.2. Non-relaxed cluster: NGC 6231

The analysis of the structure of NGC 6231, the youngest open cluster that we considered, clearly shows some mass segregation (Sect. 3.2.2).

The estimation of the cluster relaxation time gives a value of about 10^7 yr (Raboud 1997), larger than the cluster age ($3-4 \times 10^6$ yr, Raboud et al. 1997). Therefore the cluster dynamical evolution did not have enough time to produce energy equipartition among the cluster members and no mass segregation should be present. Thus we are tempted to consider that the observed mass segregation in NGC 6231 is initial and to identify it as a signature of the stellar formation processes. Within this picture, the most massive stars form near the cluster center.

However, as discussed in Raboud (1997), the computed relaxation is an upper limit. This relaxation time, calculated with the standard equations from Chandrasekhar (1942) and Spitzer & Hart (1971), refers to stars of average mass. As real clusters present a wide mass spectrum, this implies that the systems evolve on a timescale shorter than that estimated by this mean relaxation time. Furthermore, the relaxation time depends upon the location in the cluster: it significantly increases from the center to the outer regions (Mathieu 1983). Finally, N -body calculations that treat close gravitational encounters and binary formation predict more rapid dynamical evolutions than that

indicated by the mean relaxation time (Sagar et al. 1988 and references therein).

We therefore cannot exclude a dynamical evolution on shorter timescales, typically one order of magnitude, particularly in the innermost part of the cluster or for the most massive stars.

Nevertheless, the mean relaxation time is also a lower limit because we observe only the brightest stars of the cluster and therefore we underestimate the total number of stars and the characteristic radius of the cluster while we overestimate its mean stellar mass.

Numerical modelling are then truly needed to clearly quantify the amount of mass segregation due to dynamical evolution and due to the initial conditions.

Such a modelling had been done by Bonnell & Davies (1997) for the Orion Nebula Cluster (ONC), based on the data of Hillenbrand (1997a). The authors show that the position of massive stars in the center of rich young clusters cannot be due to dynamical mass segregation. In particular, they claim that for producing a Trapezium-like system within just a few crossing times, the massive stars most likely formed within the inner 10% of the cluster.

Other indications for an *initial* mass segregation, i.e. an imprint of the stellar formation processes and not a consequence of the cluster dynamical evolution, have been obtained from the observations of other very young open clusters like: NGC 3293 (Herbst & Miller 1982), NGC 6530 (McNamara & Sekiguchi 1986), IC 1805 (Sagar et al. 1988), NGC 2264, NGC 6913, NGC 654, NGC 581, Tr 1 and h and χ Per (Pandey et al. 1991). But, as these indications of initial mass segregation are mainly based on the comparison between the ages of the clusters and their mean relaxation times, these studies suffer drawbacks similar to those described above.

Clusters still embedded within their parent molecular clouds and already displaying mass segregation may be more convincing. Examples are, among others, NGC 2024 and NGC 2071 (Lada & Lada 1991). Such clusters have ages of the order of their crossing time ($\sim 10^6$ yr) or below. Relaxation processes are then negligible for them and the observed locations of their stars are close to their birthplace. Consequently, the presence of mass segregation in these *extremely* young open clusters should not result from their dynamical evolution.

All the preceding constatations favour the hypothesis that some of the mass segregation observed in a cluster as young as NGC 6231 is likely to be primordial.

Inspection of Fig. 12 also reveals that only the *most* massive stars are concentrated toward the cluster center. On the contrary, stars with masses between $\sim 20 M_{\odot}$ and $\sim 5 M_{\odot}$ are spatially well mixed. Similar results are obtained for a cluster embedded in the MonR2 molecular cloud (Carpenter et al. 1997). The authors pointed out that mass segregation may be limited to the OB stars forming in this region. Moreover, in the case of the ONC, Fig. 6 from Hillenbrand (1997b) shows very different spatial distributions for stars more massive or less massive than $5 M_{\odot}$. For masses smaller than $5 M_{\odot}$ the distributions are rather

similar. We then conclude that, in very young clusters, mass segregation likely concerns only the most massive stars.

4.2.1. Double origin for the mass segregation ?

The evolutive picture emerging from the analysis of the considered clusters (MonR2, Orion, NGC 6231, Pleiades, NGC 6705, Praesepe and M67) do not agree with the usual description of the mass segregation, as a pure consequence of dynamical evolution. We observe that the younger clusters (MonR2, Orion and NGC 6231), likely still not relaxed, already present a mass segregation and that the older ones (Praesepe, M67) present the lesser degree of mass segregation (Fig. 14a–c). Possible explanations for the last observation have been discussed in Sect. 4.1., but the presence of some mass segregation within clusters likely still not relaxed implies a reconsideration of the physical origin of this effect.

The above results allow us to propose a qualitative scenario for the evolution of mass segregation with age in open clusters:

(I) The most massive stars ($M > 20 M_{\odot}$ for NGC 6231) form near the center of clusters.

Several hypotheses could be made to explain the presence of massive stars near the center of clusters at the early beginning of their life. Either the massive protostars sink towards the center of clusters or physical conditions in the center of protostellar clouds favour the formation of massive stars. These various hypothesis are: the dynamical friction between protostellar clouds and inter-protostellar medium (Larson 1991, Gorti & Bhatt 1995, 1996); the collision and coalescence of protostellar clouds (Murray & Lin 1996); the accretion of matter, during stellar formation phases. This accretion could be faster in regions of higher temperature and turbulence (Maeder 1997), i.e. in the center of protocluster clouds, thus leading to the formation of more massive stars in these regions. This last hypothesis implies that the IMF is dependent on the local physical conditions. It is flatter in the central part of the cluster and steeper in the outer part. Therefore open clusters could be the first physical environments, observed with a sufficient spatial resolution, in which we note a non-universality of the IMF.

In the context of massive star formation in the center of clusters, it is worth noting that we observe numerous examples of multiple systems of O-stars in the center of very young open clusters. In the case of NGC 6231, 8 stars among the 10 brightest are spectroscopic binaries with periods shorter than 6 days. Moreover, we observe trapezium systems of O-stars in the ONC, NGC 6823 and Tr 37. Four-component and triple systems have also been found in NGC 2362 (van Leeuwen & van Genderen 1997) and Collinder 228 (Leung et al. 1979).

(II) In less than 10^7 yr these spatially concentrated massive stars will disappear due to stellar evolution. As they may represent a non-negligible percentage of the total mass of the cluster (between ~ 10 and 30 % in the case of NGC 6231), the disappearance of these massive stars could lead to a violent relaxation phase. If a mass segregation was previously established in the cluster it could be more or less erased during this phase, de-

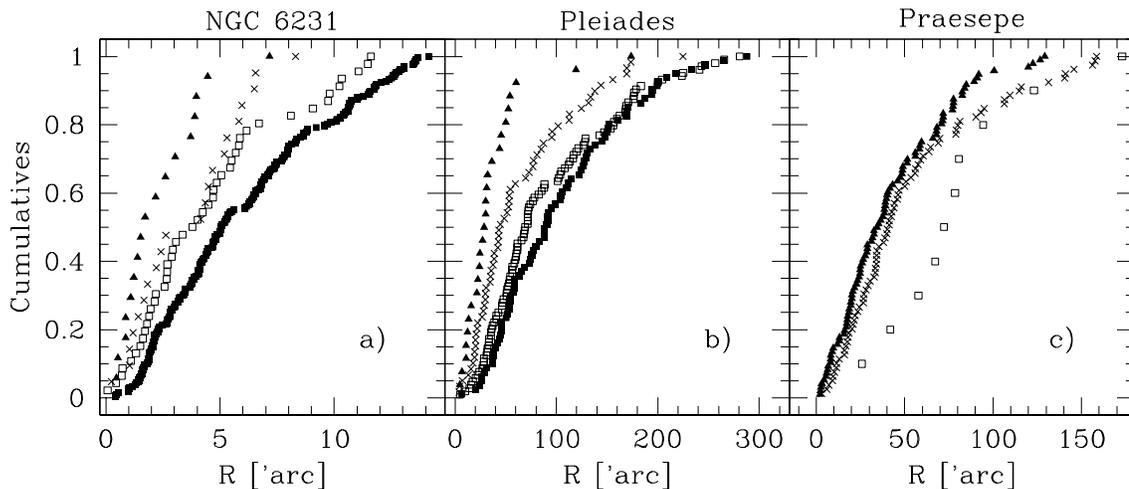


Fig. 14a–c. Cumulative distributions for stars in identical relative intervals of mass, for the three clusters. These intervals are computed relatively to the maximum stellar mass of the considered cluster. Triangles: $M \geq 0.36 \times M_{max}$; crosses: $0.23 \times M_{max} \leq M < 0.36 \times M_{max}$; open squares: $0.14 \times M_{max} \leq M < 0.23 \times M_{max}$; filled squares: $M < 0.14 \times M_{max}$. The 9 bright stars of the corona of NGC 6231 are not included in the figure.

pending on the importance of the initial population of massive stars.

We are then *possibly* left with a cluster presenting *no* mass segregation at all. NGC 6531 (Forbes 1996) provides an example of such a cluster: it is 8×10^6 yr old and does not contain any stars with masses greater than $20 M_{\odot}$ (which make up the concentrated population in NGC 6231). Forbes shows convincingly that NGC 6531 does not exhibit any mass segregation, and he explains this result by the young age of the cluster. According to him, NGC 6531 is too young for dynamical evolution to have left any significant impression. But this hypothesis was based on an estimation of the relaxation time and suffers drawbacks described in the Sect. 4.2.

Another interesting point related to the disappearance of the massive stars is the stability of the cluster. It is possible that a bound cluster becomes unbound after this violent phase. Numerical simulations by Terlevich (1987) show that clusters with flat initial mass functions have to be rich enough to survive the initial violent period of mass loss.

(III) The last point of our scenario is that all mass segregation observed in older clusters (like the Pleiades or Praesepe) is *merely* the consequence of the cluster’s *dynamical evolution*. However, this conclusion does not imply that NGC 6231 is a representative precursor of older clusters.

To better quantify this hypothesis of a possible double origin (initial and dynamical) of the mass segregation we need to analyse the structure of open clusters just old enough (around 10^7 yr) to have lost their most massive stars. Thus, one consequence of our hypothesis is that some of these clusters, those which initially contained an important population of massive stars, should not present any mass segregation.

5. Conclusion

We present a study of the structure of Praesepe and NGC 6231. The results obtained, compared with the Pleiades (RM98) and other clusters (Orion, Hillenbrand 1997a, b, Bonnell & Davies 1997; MonR2, Carpenter et al. 1997; M11, Mathieu 1984; M67, Mathieu 1985) are used to discuss the mass segregation within open clusters.

The study of the Praesepe structure has been performed on the basis of the presently available data which limits the sample to stars brighter than $V = 12$. We used the best present knowledge on duplicity in Praesepe. Using an asymmetry estimator applied to the apparent stellar positions we find that the outer parts of Praesepe are round-shaped. This could be either real or only the effect of projection.

Praesepe is the second cluster (after the Pleiades in RM98) for which the mass function of single stars and primaries of multiple systems have been determined separately and compared. They turned out to be different.

We have observed mass segregation among cluster members (singles or multiples) which does not depend on the binary periods. Consequently, binaries are more concentrated than single stars and massive binaries are more concentrated than less massive ones. However, the surprising result is that the mass segregation observed in Praesepe (in the mass range $1.5\text{--}2.3 M_{\odot}$) is less obvious than in the Pleiades, although the former cluster is older.

Mass segregation is also observed in the very young open cluster NGC 6231. As NGC 6231 is likely still not relaxed, this observation implies that the origin for the mass segregation is possibly independent of the cluster dynamical evolution. Moreover, we observe that only the most massive stars ($M > 20 M_{\odot}$, in NGC 6231) are centrally concentrated. The intermediate mass intervals are spatially well mixed.

We therefore suggest that mass segregation observed in very young open clusters concerns only the most massive stars and is mainly the signature of stellar formation processes, implying a locally non-universal IMF, or of intra-cloud early dynamical evolution. These massive stars disappear in less than 10^7 yr and this phenomenon could lead to a violent relaxation phase, if the population of massive stars is important. Then clusters with ages of the same order of magnitude could present temporarily no mass segregation (like in NGC 6531, Forbes 1996), until dynamical evolution becomes responsible for the settlement of mass segregation in older, relaxed, clusters. In the oldest clusters, where the mass spectrum is much narrower, only mass segregation between binaries and single stars should be observable.

Therefore it appears important to underline that one cannot speak of mass segregation in general, but one should indicate for each cluster which kinds of stars are concentrated and which are not.

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