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MASS SEGREGATION IN VERY YOUNG OPEN CLUSTERS

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RESUMEN

El estudio del cúmulo abierto muy joven NGC 6231 muestra claramente la presencia de segregación de masas para las estrellas de masas superiores. Estas observaciones, en combinación con las efectuadas para otros objetos jóvenes, y recientes simulaciones numéricas, ofrecen fuerte sustento a la hipótesis de un origen inicial para la segregación de masas de las estrellas de masas superiores. Estos resultados llevan a la conclusión de que tales estrellas se forman cerca del centro de los cúmulos, lo cual representa un fuerte condicionamiento para los escenarios de formación de estrellas y cúmulos estelares.

ABSTRACT

The study of the very young open cluster NGC 6231 clearly shows the presence of a mass-segregation for the most massive stars. These observations, combined with those concerning other young objects, and very recent numerical simulations, strongly support the hypothesis of an initial origin for the mass-segregation of the most massive stars. These results led to the conclusion that massive stars form near the center of clusters. They are strong constraints for scenarii of star and stellar cluster formation.

Key words: **OPEN CLUSTERS: DYNAMICAL EVOLUTION — OPEN CLUSTERS: GENERAL — OPEN CLUSTERS: INDIVIDUAL (NGC 6231)— OPEN CLUSTERS: STRUCTURE**

1. INTRODUCTION

The aim of the present work is to give observational constraints for a better understand of the dynamical evolution of open clusters (OCs). For an analysis of this evolution, the observation and study of clusters of different ages is required. In order to fix the "initial conditions" we chose to extensively observe NGC 6231, which is a rich and very young OC: it has an age of 3 – 4 Myr and contains more than one hundred O and B stars (Raboud 1996; Raboud, Cramer, & Bernasconi 1997). The data collected allowed us to complete the analysis of the cluster structure (Raboud 1997; Raboud & Mermilliod 1998, RM98).

2. DISCUSSION

The main result of our study is the observation of mass-segregation in NGC 6231, which can be clearly seen in Fig. 1. Being NGC 6231 a very young OC, it was important first to solve the problem of the origin of the mass-segregation: is it *initial* (i.e., the imprint of the stellar formation processes) or is it the consequence of the dynamical evolution of the cluster?

As first step towards the understanding of this problem we computed the mean relaxation time (t_r) of the cluster. Using the standard equations from Chandrasekhar (1942) and Spitzer & Hart (1971) we derived a value of $t_r \approx 10^7$ yr. This result is a lower limit because we observed only the brightest stars of the cluster and therefore underestimated the total number of stars and the characteristic radius of the cluster while overestimating its mean stellar mass. As the age of the cluster is nearly one order of magnitude smaller than its t_r, we conclude that the observed mass segregation in NGC 6231 is an imprint of the stellar formation processes.

Nevertheless, the preceding conclusion is dependent on the physical validity of the *mean* t_r. This time 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 t_r. Furthermore, t_r depends upon the location in the cluster: it significantly increases from the center to the outer regions. Moreover, N-body calculations that treat close gravitational encounters and binary formation predict more rapid dynamical evolutions, typically one order of magnitude, than that indicated by the mean t_r. Therefore, t_r has to be an upper limit and the conclusion stated above that the observed mass segregation in NGC 6231 is not a consequence of the dynamical evolution of the cluster is strongly weakened.

However, numerous other pieces of observational evidence for initial mass segregation in OCs exist in the Galaxy and the LMC. But, as these "proofs" are mainly based on the comparison between the age of the cluster and its mean t_r, these studies suffer drawbacks similar to those described above.

Then, what would be the solutions to unambigously reveal an *initial* mass segregation? There are two possibilities: observational **(a)** and numerical **(b)**.

(a) From the observational point of view we have to observe not only very young OCs but also *extremely* young OCs, i.e., clusters with ages of the order of their crossing time or below. In such clusters relaxation processes have no meaning and the observed locations of the stars are close to their birthplace. Examples are, among others, NGC 2024 and NGC 2071 (Lada & Lada 1991). These clusters are still embedded in their parental cloud and already present a mass segregation.

(b) From the numerical point of view we could simulate a cluster and test if an observed mass segregation could possibly be explained by relaxation processes or if we need the "help" of an initial segregation. Such a modelling had been done by Bonnell & Davies (1998) for the Orion Nebula Cluster (ONC). 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.

These last considerations tend to favor the reality of, at least partially, initial mass segregation in very young OCs. This result implies that the IMF is, locally, not unique. We observe its variation: it is flatter in the central part of the cluster and steeper in the outer part.

Furthermore, a closer inspection of Fig. 1 reveals that only the most massive stars ($M > 16\ M_\odot$) are clearly concentrated toward the cluster center. The stars belonging to the two intermediate mass intervals ($6 < M < 16\ M_\odot$) are spatially well mixed. Similar results are obtained for a cluster embedded in the Mon R2 cloud (Carpenter et al. 1997). Moreover, in the case of the ONC, Fig. 6 from Hillenbrand (1997) 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.

3. CONCLUSION: DOUBLE ORIGIN FOR THE MASS SEGREGATION?

The above results allow us to propose a qualitative scenario for the evolution of mass segregation with age in OCs (RM98):

(I) The most massive stars form in the center of clusters.
Several hypotheses could be made to explain this phenomenon: dynamical friction between protostellar clouds and inter-protostellar medium (Larson 1991; Gorti & Bhatt 1995, 1996); 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.

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 OCs. 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 and Collinder 228.

(II) In less than 10^7 yr these spatially concentrated massive stars will disappear due to stellar evolution. As they 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, depending on the importance of the initial population of massive stars.

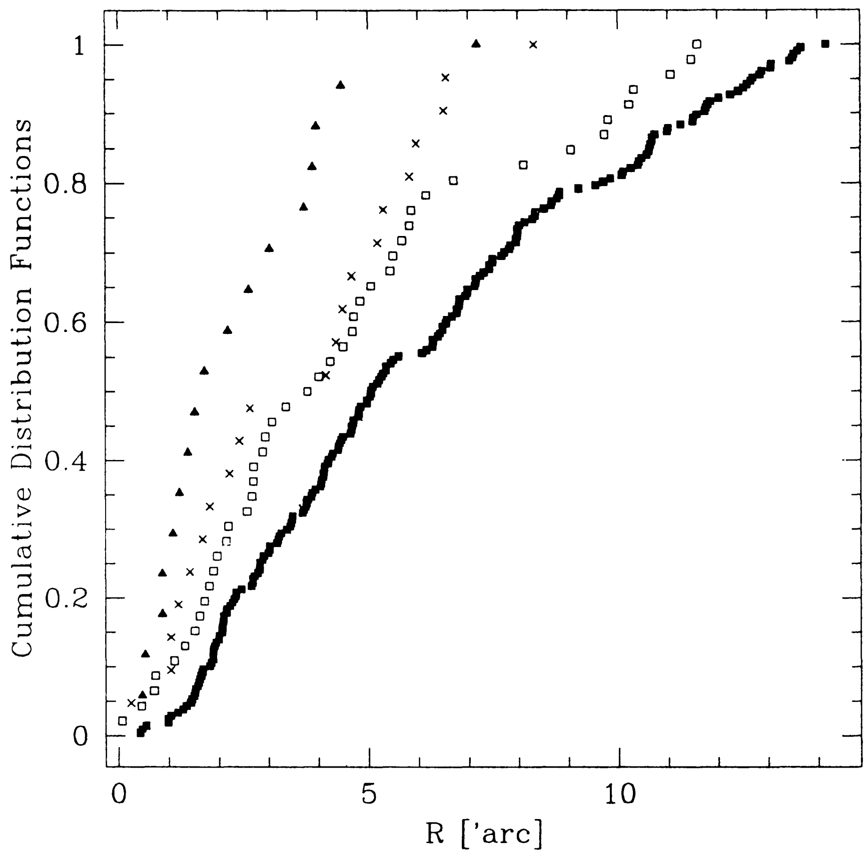

Fig. 1. Cumulative distributions for stars of different mass intervals, as a function of the distance to the center of the cluster NGC 6231. The most massive stars are more concentrated toward the cluster center. Triangles: $M > 16\ M_{\odot}$, crosses: $10 < M < 16\ M_{\odot}$, open squares: $6 < M < 10\ M_{\odot}$, filled squares: $M < 6\ M_{\odot}$.

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 his observation 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 t_r and suffers the drawbacks described in the Discussion.

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 is *merely* the consequence of the cluster's *dynamical evolution*.

To better quantify this hypothesis of a possible double origin (initial and dynamical) of the mass segregation we need to analyse the structure of OCs 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.

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