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The origin of mass segregation in NGC 3603

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Abstract. NGC 3603 is one of the most massive, compact young star clusters in the Milky Way. The cluster has an age of only about 1 Myr and is embedded in a giant molecular cloud with ongoing star formation. We have analyzed deep imaging data obtained with the Wide Field and Planetary Camera 2 aboard the *Hubble Space Telescope*. We have obtained two epochs separated by 10 years, from which we derived proper motions which we used to determine cluster membership. After the removal of field stars, the resulting color–magnitude diagram shows a main sequence in addition to another clear sequence of pre-main-sequence stars. The cluster shows pronounced mass segregation and appears to have a very short crossing timescale. Our photometric, astrometric and kinematic data help us to evaluate the dissolution timescale of NGC 3603 and whether the mass segregation is likely to be primordial or evolutionary.

Keywords. galaxies: star clusters, Galaxy: kinematics and dynamics

1. Introduction

The NGC 3603 giant molecular cloud in the Carina spiral arm contains one of the most massive, young compact clusters in the Milky Way. This is the HD 97950 star cluster, which is often referred to by the NGC number of the surrounding, extended structure. The cluster has an age of approximately 1 Myr. This makes it an interesting target to study the open question of the impact of primordial versus dynamical mass segregation, assuming that dynamical effects would not yet have had enough time to significantly alter the young cluster's structure. Another interesting question is that of the duration of star formation in star clusters. It is commonly assumed that such objects do not show any appreciable age spread, but that all stars formed in one single, brief burst. Very young clusters may permit us to investigate the duration of such a burst of intense star formation.

2. Observations and data reduction

Deep imaging data of NGC 3603 were obtained repeatedly with the Wide Field and Planetary Camera 2 (WFPC2) aboard the *Hubble Space Telescope*. One set of observations was obtained in 1997 using the F547M, F675W and F814W filters. The other set was observed in May 2007 using the F555W, F675W and F814W filters. In both cases, the cluster center is located on the high-resolution PC chip. The 10 years of epoch difference provide us with the opportunity of obtaining the cluster's proper motion.

Both sets of data were reduced using HSTphot (Dolphin 2000), a program developed for crowded-field stellar photometry of WFPC2 data. The incompleteness in the central regions of the cluster turned out to be fairly high due to high stellar densities and a concentration of very luminous stars in the center. We identified 445 common stars on the PC chip in the exposures of the two epochs. Here, we only concentrate on the PC chip ($r \sim 20''$) for which there is ~ 90 percent overlap between two epochs. Also, with $\sim 0.05''$ pixel^{-1}, the PC chip has twice the resolution of the three other chips.

3. Results

3.1. *Proper motion*

By comparing the position of common stars between the two epochs, we derived relative proper motions for these stars. These proper motions help us to select cluster members quite effectively, since the cluster stars have a smaller proper motion than the largely much closer field stars. The resulting relative proper-motion distribution of member stars on the PC chip is shown in Figure 1. The uncertainty in the proper motion is on average 0.05 pixels, corresponding to a velocity of 9 km s^{-1}.

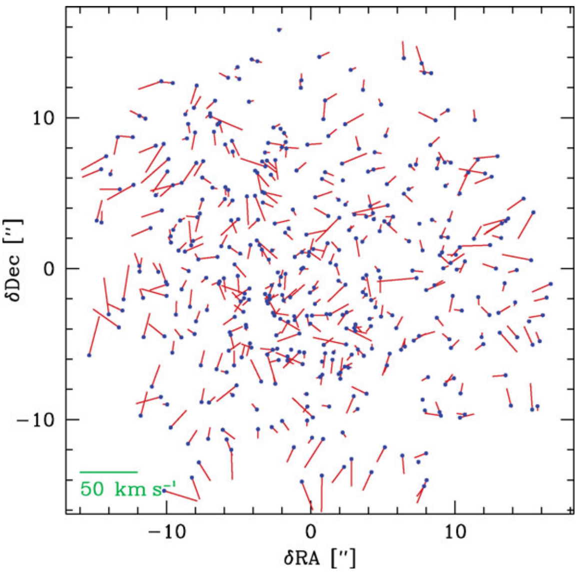

Figure 1. Map of measured proper motions of member stars on the PC chip. Each filled dot represents the position of a cluster member star. The lines point in the direction of the proper motion.

The color–magnitude diagram (CMD) of the proper-motion-selected cluster member stars shows a well-populated main sequence (MS) and pre-main sequence (PMS). From isochrone fitting we find an age of $\sim$ 1 Myr for the MS and PMS stars. The wide distribution of PMS stars suggests a possible age spread of up to 3 Myr.

3.2. *Mass function*

The mass function (MF) of NGC 3603 was derived only for member stars on the PC chip. We count stars in absolute V-magnitude bins spaced such that we cover mass bins with a logarithmic bin size of 0.2 mag to measure the MF of NGC 3603. Using the same method as applied by Grebel & Chu (2000), we find the absolute magnitude corresponding to the mass bins using isochrones of solar metallicity and an age of 1 Myr. For the MS stars we chose an isochrone from Lejeune & Schaerer (2001), while for the PMS stars we used Siess *et al.* (2000). The center of NGC 3603 is severely affected by crowding and by additional incompleteness introduced by the saturation of luminous stars. The incompleteness was quantified by magnitude- and position-dependent artificial-star experiments and corrected for.

Fitting the corrected number counts for MS and PMS stars detected on the PC chip within the mass range of 1–100 $M_\odot$ (Figure 2) results in a MF slope of $\Gamma = -0.95 \pm 0.21$. Our result agrees well with the earlier studies of Sung *et al.* (2004) and Stolte *et al.* (2006). Even though the low-mass end of our MF is unreliable due to low completeness (lower than 50%), it follows the slope of the more massve stars very well.

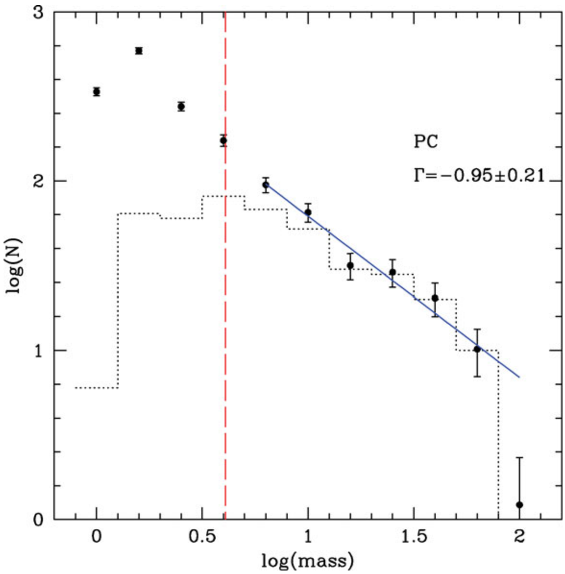

Figure 2. Mass function of all cluster member stars on the PC chip. The vertical dashed line indicates a completeness limit of 50%. The solid line is the linear least-squares fit to points above the 50% completeness limit. The resulting slope of the MF is $\Gamma = -0.95 \pm 0.21$.

3.3. *Dynamical status of NGC 3603*

As already observed in earlier studies (Nürnberger *et al.* 2002; Grebel 2004; Stolte *et al.* 2006; Harayama *et al.* 2008), NGC 3603 shows significant mass segregation. Mass segregation is also observed in the young star clusters ONC (Orion Nebula Cluster; Hillenbrand & Hartmann 1998), NGC 2244 and NGC 6530 (Chen *et al.* 2007). In Figure 3, we show the radial variation of the NGC 3603 MF as measured in different annuli around the cluster center. The MF slope increases as we move outwards, revealing the presence of more massive stars in the center compared to the outskirts of the cluster. However, the origin of this mass segregation is still under debate. Bonnell & Davies (1998) ran simulations of an ONC-like cluster to investigate the timescale of mass segregation. It turned out that the timescale needed for dynamical mass segregation is longer than the ONC's age, probably $\sim 3t_{\rm cross}$. Massive stars need to have originated within the innermost 10% of the stellar distribution if they are to form a Trapezium-like object within $3 - 5\,t_{\rm cross}$. Other work by Moeckel & Bonnell (2000) ran simulations with initial conditions of 'no initial segregation,' 'moderate initial segregation,' 'heavy initial segregation' and 'only massive stars segregated.' By comparing the simulation results with the observations for the ONC and NGC 6231, the simulations with 'only massive stars segregated' appeared to be consistent with the available observational data.

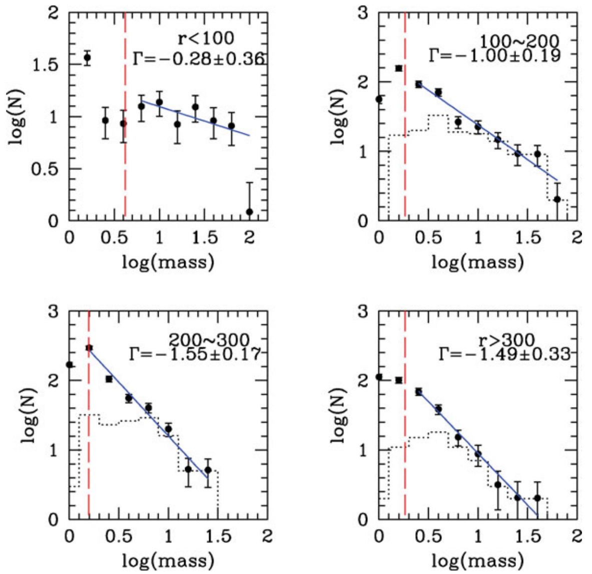

Figure 3. Radial variation of the MF of all member stars on the PC chip measured in different annuli. The dashed line is the 50% completeness limit. The solid lines are weighted linear least-squares fits to the data points above the 50% completeness limit.

To investigate the origin of mass segregation, we calculate the mean tangential velocity for the same annuli as in Figure 3. Figure 4 shows the distribution of tangential velocities of all member stars on the PC chip. There is a slight indication for increasing velocities beyond a radius of 280 pixels, but considering the size of the error bars this may not be significant. The velocity dispersion converted from proper motions is $\sigma = 3.44$ km s^{-1}. If we assume an isotropic distribution, the intrinsic velocity dispersion of NGC 3603 is $\sigma_{\rm int} = 4.87$ km s^{-1}, which is larger than that of the ONC (2.5 km s^{-1}; Bonnell & Davies 1998). Van den Bergh (1979) derived an even larger heliocentric radial velocity for NGC 3603 of about 6 km s^{-1}. Harayama *et al.* (2008) found a core radius of ~ 0.14 pc. Combining $\sigma_{\rm int}$ with this estimate, the cluster crossing timescale is 3×10^4 yr. In other words, the age of NGC 3603 is almost 30 $t_{\rm cross}$. According to the simulations of Bonnell & Davies (1998), this is long enough to produce significant mass segregation through dynamical evolution.

The relaxation timescale from Binney & Tremaine (1987) can differ for very massive stars to low-mass stars. For NGC 3603, which contains stellar masses from subsolar to about 100 M$_\odot$, the relaxation timescale will differ dramatically for different stellar masses. Stars of 1 M$_\odot$ will have a relaxation timescale on the order of 10^6 yr, but for 100 M$_\odot$ stars it will be on the order of 10^4 yr. Hence, massive stars would already have undergone dynamical evolution while less massive stars are still little affected. Allison *et al.* (2009) also found that the dense cores of clusters can mass segregate within $\sim 0.1 - 0.2$ Myr, which for NGC 3603 corresponds to about 10–20 crossing times. Moreover, these authors concluded that this time is sufficient to mass segregate the most massive stars and that a cluster can dynamically segregate stars above 2–4 M$_\odot$. Consequently, this mass-segregation time already amounts to ~ 10 crossing times of the NGC 3603 core, so that this cluster is actually dynamically old. Given these estimates, it is therefore reasonable to assume that massive stars already sank to the center of NGC

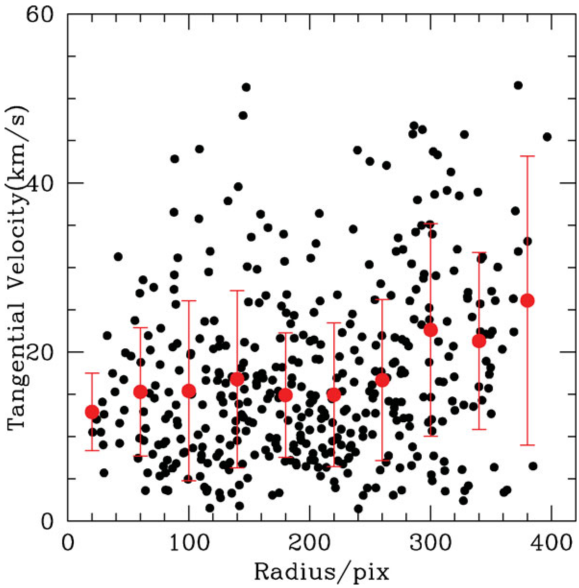

Figure 4. Tangential velocity distribution of all member stars on the PC chip. The small black dots indicate stars. The larger dots with error bars show the mean tangential velocity in each annulus. The radius of each annulus is 40 pixels.

3603 as a result of dynamical evolution. For low-mass stars, on the other hand, it is still difficult to distinguish primordial and evolutionary effects.

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