ON THE ORIGIN OF MASS SEGREGATION IN NGC 3603

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ABSTRACT

We present deep Hubble Space Telescope/Wide Field and Planetary Camera 2 photometry of the young HD 97950 star cluster in the giant H II region NGC 3603. The data were obtained in 1997 and 2007 permitting us to derive mass segregated properties based on proper motions of the stars. Our data are consistent with an age of 1 Myr for the HD 97950 cluster. A possible age spread, if present in the cluster, appears to be small. The global slope of the incompleteness-corrected mass function for member stars within 60″ is \( \Gamma = -0.88 \pm 0.15 \), which is flatter than the value of a Salpeter slope of \(-1.35\). The radially varying mass function shows pronounced mass segregation ranging from slopes of \(-0.26 \pm 0.32\) in the inner \(5″\) to \(-0.94 \pm 0.36\) in the outermost annulus (40″–60″). Stars more massive than \(50 M_\odot\) are found only in the cluster center. The \(\Lambda\) minimum spanning tree technique confirms significant mass segregation down to \(30 M_\odot\). The dependence of \(\Lambda\) on mass, i.e., that high-mass stars are more segregated than low-mass stars, and the (weak) dependence of the velocity dispersion on stellar mass might imply that the mass segregation is dynamical in origin. While primordial segregation cannot be excluded, the properties of the mass segregation indicate that dynamical mass segregation may have been the dominant process for segregation of high-mass stars.

Key words: ISM: individual objects (NGC 3603) – open clusters and associations: individual (HD 97950) – stars: kinematics and dynamics – stars: luminosity function, mass function – stars: massive – stars: pre-main-sequence

Online-only material: color figures, machine-readable tables

1. INTRODUCTION

The compact HD 97950 cluster in the luminous giant H II region NGC 3603 is one of the most massive young star clusters in the Milky Way. As the closest and densest starburst cluster accessible at optical wavelengths, it has been subject to many studies during the past few decades. The cluster contains three Wolf-Rayet (WR) stars and up to 50 O-type stars (Drissen et al. 1995). Its total mass is estimated to be \(\sim 10^4 M_\odot\) (Harayama et al. 2008) with an upper dynamical mass limit of \(17,600 \pm 3800 M_\odot\) (Rochau et al. 2010). The WR stars show characteristics of WN6 stars, but also have Balmer absorption lines (Drissen et al. 1995), suggesting that these stars are actually core hydrogen burning rather than evolved stars (Conti et al. 1995; de Koter et al. 1997). Two of these three WR stars are very close binaries (Schnurr et al. 2008).

Based on stellar spectral types, Melena et al. (2008) argue that the most massive stars in the HD 97950 cluster are coeval with ages of 1–2 Myr, while less massive stars (20–40 \(M_\odot\)) show a somewhat larger age spread of up to 4 Myr. Recent photometric studies have arrived at a range of ages from an essentially single-burst population of 1 Myr (e.g., Sung & Bessell 2004; Stolte et al. 2004; Kudryavtseva et al. 2012) to 2–3 Myr (Eisenhauer et al. 1998; Harayama et al. 2008). The stars in the cluster outskirts may be slightly older (~5 Myr according to Sung & Bessell 2004), as is also suggested by spectroscopic studies of the late O- and early B-type supergiants outside the core of the HD 97950 cluster (Melena et al. 2008). These evolved supergiants are probably not physically connected with HD 97950 owing to their advanced evolutionary state (e.g., Sher 25, see Brandner et al. 1997a, 1997b) and higher age (Crowther et al. 2008; Melena et al. 2008). They may even indicate the occurrence of multiple episodes and possibly sequential star formation NGC 3603 (e.g., Moffat 1983; Melnick et al. 1989; De Pree et al. 1999; Tapia et al. 2001). Beccari et al. (2010) suggest an extended star formation episode of up to 10–20 Myr as indicated by an apparent age spread in pre-main-sequence (PMS) stars in NGC 3603.

Despite its young age, the HD 97950 cluster shows pronounced mass segregation (e.g., Sung & Bessell 2004; Grebel & Gallagher 2004). Mass segregation is often observed in young star clusters (e.g., in the ONC, Hillenbrand & Hartmann 1998; Hillenbrand & Hartmann 1998; Arches, Stolte et al. 2002; NGC 6611, Bonatto et al. 2006; NGC 2244 and NGC 6530, Chen et al. 2007; Schilbach et al. 2006), but the origin of mass segregation is still unclear. Bonnell & Davies (1998) argue that clusters cannot dynamically segregate in only a few Myr and so mass segregation in young clusters must be primordial.

Whether mass segregation is primordial or dynamical is an important constraint on theories of massive star formation and cluster formation and evolution. The competitive accretion theory (Bonnell et al. 2001; Bonnell & Bate 2006) suggests that protostars in the dense central regions of a young star
cluster can accrete more material than those in the outskirts and that therefore primordial mass segregation would be a natural outcome of massive star formation. However, if mass segregation can occur dynamically on a very short timescale then massive star formation can occur anywhere in a cluster, possibly monolithically (e.g., Krumholz et al. 2009).

McMillan et al. (2007) show that young mass-segregated clusters may be the result of mergers between small clumps that are mass segregated by either primordial or dynamical means. Allison et al. (2009a, 2010) suggest that observations support that clusters form with initial substructure, and that show for clusters with initially cool (subvirial) and clumpy distributions dynamical mass segregation can occur very rapidly in the cluster’s core after it has collapsed (∼0.5–1 Myr). In contrast to smooth, subvirial clusters, clumpy clusters collapse to much higher densities, enabling fast dynamical segregation.

The initial conditions of star clusters and the origin of mass segregation place important constraints on theories of massive star formation and cluster evolution. In the case of dynamical segregation, mass segregation is expected to be observable down to some “limiting mass” that is proportional to the dynamical timescale (Allison et al. 2009a, 2010). This appears to be the case in, e.g., the Orion Nebula Cluster (ONC, ∼1 Myr), which was found to be mass segregated down to 5M⊙ using the minimum spanning tree (MST) method (Allison et al. 2009b). Discussing the different methods commonly used to evaluate mass segregation in star clusters, Olszak et al. (2011) argue that the MST method is superior to the other methods since it does not make assumptions about symmetry or the location of the center of the distribution nor is it affected by uncertainties introduced by binning (see also Allison et al. 2009b; Küpper et al. 2011).

Here we analyze Hubble Space Telescope (HST) observations of the massive HD 97950 cluster in NGC 3603 obtained with the Wide-Field Planetary Camera 2 (WFPC2). In Section 2 we summarize the observations and data reduction. In Section 3 we discuss the color–magnitude diagram (CMD) of the HD 97950 cluster. In Section 4 we infer the present-day mass function and discuss evidence for mass segregation based on the traditional mass function analysis in concentric annuli. Afterward, we refine and quantify the mass segregation using an MST analysis. In Section 5, we investigate the origin of the mass segregation in the cluster with kinematic data (tangential velocity and velocity dispersion). We argue that dynamical processes are the dominant mechanism for the mass segregation in the cluster in Section 6. We present our conclusions and summary in Section 7.

2. OBSERVATIONS AND DATA REDUCTION

For our analysis of the HD 97950 cluster in NGC 3603 we used deep imaging data obtained with HST/WFPC2. The first observations were carried out in 1997 July (program GO 6763, PI: Drissen). The Planetary Camera (PC) chip was centered on the cluster. We obtained shallow, intermediate, and long exposures ranging from fractions of a second to 20–30 s in the F547M and F814W filters, respectively. Details are given in the exposure time log in Table 1. Earlier results from analyses of these data were presented by Sung & Bessell (2004) and by Grebel & Gallagher (2004).

The second data set was obtained in 2007 September (program GO 11193, PI: Brandner). The longest exposures lasted 100 s (F555W) and 160 s (F814W), considerably longer than in 1997 (Table 1). The 10 year epoch difference between the first and the second data set permits us to infer cluster membership using proper motions. Preliminary results of this analysis were presented by Pang et al. (2010). Rochau et al. (2010) published a proper motion study of the same data set.

Both data sets were reduced using HSTphot (Dolphin 2000, 2005), a program developed for crowded-field stellar photometry of WFPC2 data. The shifts between the dithered images were determined following Koekemoer et al. (2002).

Stars at cluster-centric distances of 20′–60′ are located on the three Wide Field Camera (WFC) chips in our data. While both in 1997 and 2007 the PC chip was centered on the HD 97950 cluster, the two pointings are rotated by 51° with respect to each other. Thus the WFC chips only have 13% overlap, whereas the common area covered by the PC chip exposures from the two epochs amounts to ∼90%.

We only use images obtained in the filters either common to both data sets (F814W) or at comparable wavebands (F547M in the 1997 data set and F555W in the 2007 data set). Conveniently, HSTphot transforms magnitudes in these filters into the V and I bands in the standard Johnson–Cousins system. We found 571 common stars on the PC and WFC chips within the cluster radius of ∼60′ (Sung & Bessell 2004) observed in both epochs. The magnitudes of the common stars are taken from the 1997 photometry. The position–magnitude-dependent incompleteness in the detection of point sources was assessed through artificial star experiments.

Proper motions were derived using common stars observed in the same filter during the two epochs in order to select likely cluster members and to weed out field stars. The membership of stars in the cluster is determined by fitting a two-Gaussian model to the proper motion distribution. We select only stars with membership probabilities larger than 0.7 to be cluster members (Jones & Walker 1988), which are retained in the subsequent analysis (see Tables 2–4). Fifty-nine stars on the PC and WFC chips (10% of the total number of common stars) were thus eliminated as foreground stars.

Because of the decreasing stellar density with increasing cluster radius the fractional foreground contamination increases with radius as well. Because of the high extinction in the NGC 3603 giant H ii region, we may assume that background stars are effectively obscured and do not significantly contribute to our measurements. However, giant H ii regions often show a complex age structure (e.g., Grebel & Chu 2000), and Beccari et al. (2010) found older PMS stars in a wide area around the cluster. Hence we cannot exclude the presence of older stars belonging to NGC 3603 that would be difficult to disentangle from younger cluster stars at the same distance via proper motions.

| Table 1 | Exposure Time Log of the HST/WFPC2 Observations of the HD 97950 Cluster |
|---------|-------------------------------------------------------------|
| Filter  | Shallow Exposures (s) | No. of Frame | Median Exposures (s) | No. of Frame | Deep Exposures (s) | No. of Frame |
| F547M   | 1                  | 3           | 10                   | 12          | 30                   | 8           |
| F814W   | 0.4                | 3           | 5                    | 12          | 20                   | 8           |
| F555W   | 0.4                | 4           | 26                   | 4           | 100                  | 4           |
| F814W   | …                  | …           | 18                   | 4           | 160                  | 4           |
Table 2: The VI Photometry and Relative Proper Motions of the Member Stars on the PC Chip of WFPC2

| No. | X      | Y      | V      | I      | r  | μx     | μy     |
|-----|--------|--------|--------|--------|----|--------|--------|
|     | (mas)  | (mas)  | (mas)  | (mas)  | (")| (mas yr⁻¹) | (mas yr⁻¹) |
| 1   | 430.97 | 515.83 | 15.31  | 15.79  | 4.16| −0.32063 | 0.42928 |
| 2   | 707.94 | 502.85 | 15.24  | 13.60  | 13.74| −0.37145 | −0.52531 |
| 3   | 79.76  | 548.09 | 15.25  | 16.59  | 16.95| −0.06742 | 0.05419 |
| 4   | 385.40 | 354.77 | 15.10  | 13.60  | 3.63 | 0.05419  | 0.22629 |
| 5   | 444.91 | 284.16 | 15.25  | 13.71  | 6.64 | 0.14993  | −0.08465 |

Notes. X and Y are star positions in pixel coordinates on the PC chip of WFPC2 based on the 2007 data. r is the cluster-centric distance in arcseconds. μx and μy are relative proper motions' components along the x and y directions of (PC) pixel coordinates (2007). V and I magnitudes are from the 1997 WFPC2 data. This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.

Table 3: The VI Photometry and Relative Proper Motions of the Member Stars on the WFC2 Chip of WFPC2

| No. | X      | Y      | V      | I      | r  | μx     | μy     |
|-----|--------|--------|--------|--------|----|--------|--------|
|     | (mas)  | (mas)  | (mas)  | (mas)  | (")| (mas yr⁻¹) | (mas yr⁻¹) |
| 1   | 550.24 | 101.76 | 16.91  | 17.31  | 41.30| −0.08060 | −0.16502 |
| 2   | 719.24 | 79.45  | 17.27  | 15.20  | 52.46| −0.16724 | −0.10483 |
| 3   | 568.64 | 183.71 | 15.93  | 15.37  | 47.85| −0.38513 | 0.75699 |
| 4   | 306.83 | 94.90  | 18.51  | 16.65  | 28.67| −0.27374 | 0.03670 |
| 5   | 570.07 | 323.19 | 18.77  | 17.02  | 57.72| −0.17029 | −0.17359 |

Notes. X and Y are star positions in pixel coordinates on the WFC2 chip of WFPC2 based on the 2007 data. r is the cluster-centric distance in arcseconds. μx and μy are relative proper motions' components along the x and y directions of (WFC2) pixel coordinates (2007). V and I magnitudes are from the 1997 WFPC2 data. This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.

Table 4: The VI Photometry and Relative Proper Motions of the Member Stars on the WFC4 Chip of WFPC2

| No. | X      | Y      | V      | I      | r  | μx     | μy     |
|-----|--------|--------|--------|--------|----|--------|--------|
|     | (mas)  | (mas)  | (mas)  | (mas)  | (")| (mas yr⁻¹) | (mas yr⁻¹) |
| 1   | 331.16 | 211.81 | 17.89  | 14.87  | 48.98| −0.07019 | 0.22038 |
| 2   | 194.24 | 169.76 | 17.31  | 15.33  | 36.84| −0.16998 | 0.34409 |
| 3   | 121.32 | 188.19 | 18.00  | 16.17  | 30.16| −0.44304 | 0.15900 |
| 4   | 331.39 | 242.91 | 18.56  | 16.51  | 49.10| −0.24994 | 0.64194 |
| 5   | 362.65 | 200.63 | 18.88  | 16.99  | 51.83| 0.24292  | 0.54993 |

Notes. X and Y are star positions in pixel coordinates on the WFC4 chip of WFPC2 based on the 2007 data. r is the cluster-centric distance in arcseconds. μx and μy are relative proper motions' components along the x and y directions of (WFC4) pixel coordinates (2007). V and I magnitudes are from the 1997 WFPC2 data. This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.

3. COLOR–MAGNITUDE DIAGRAMS AND AGE

Figure 1 shows the CMDs of the HD 97950 cluster including all common stars measured in the two epochs in the cluster core (PC: 20°, left panel) and within the cluster radius (∼60°, Sung & Bessell 2004; PC & WFCs, right panel). The CMDs show a steep main sequence (MS) on the PC and a broader MS (at the faint end) when the WFCs are included. The contamination of foreground stars is more severe for the WFCs (gray dots) since they cover a larger area. There is a broad region of redder PMS stars and a wide transition region between the MS and the PMS in both CMDs. Like Harayama et al. (2008), we do not see clear evidence of a sequence of equal-mass binaries as earlier suggested by Stolte et al. (2004).

Figure 5 in Sung & Bessell (2004) shows that E(B − V) stays unchanged with 1.25 mag within 30° (see also Moffat 1983). We adopt a reddening law of E(V − I)/E(B − V) = 1.45±0.05 and E(B − V) = 1.25 from Sung & Bessell (2004), and assume a uniform extinction of A_V = 4.44 ± 0.15 (R_V = 3.55) throughout the region within r ≤ 60°. The reddening corrected MS on the PC aligns with that on the WFCs (right panel of Figure 1), indicating that our adoption is reasonable.

In order to derive stellar masses along the MS, we use the isochrone models of Lejeune & Schaerer (2001). These isochrones extend to masses above 100 M_⊙, appropriate for the HD 97950 cluster (see Schnurr et al. 2008; Crowther et al. 2010). For the PMS stars on WFPC2 images, for which the mass goes down to 0.8 M_⊙ (Drissen 1999), we use Siess et al. (2000) isochrones, which cover a larger mass range (0.1–7.0 M_⊙) than other PMS isochrones. We adopt a distance of d = 6.9 ± 0.6 kpc from Sung & Bessell (2004) and solar metallicity for the HD 97950 cluster (see Hendry et al. 2008) throughout this paper.

The MS of HD 97950 is well represented by a Lejeune & Schaerer 1 Myr isochrone (Figure 1). Slightly older MS isochrones also provide a good fit, in agreement with spectroscopic age estimates for the massive stars. The Siess isochrones provide a good fit, in agreement with spectroscopic age estimates for the massive stars. The Siess isochrones also provide a good fit, in agreement with spectroscopic age estimates for the massive stars. The Siess isochrones also provide a good fit, in agreement with spectroscopic age estimates for the massive stars. The Siess isochrones also provide a good fit, in agreement with spectroscopic age estimates for the massive stars.

(A color version of this figure is available in the online journal.)
region where PMS stars join the MS we find a broad range of luminosities ($16 \lesssim V \lesssim 19$), which either again indicates an age spread or is due to the presence of (MS) stars with surviving circumstellar disks (Stolte et al. 2004).

Non-accreting isochrones, e.g., the Siess isochrones, tend to overestimate the stellar ages for stars whose effective temperature is above 3500 K (Hosokawa et al. 2011). Baraffe et al. (2009) suggest that the apparent spread of the PMS stars in the Hertzsprung–Russell diagram at ages of a few Myr can be plausibly attributed to a spread in the stellar radius and a different episodic accretion history, instead of an age range as inferred from non-accreting stellar evolutionary models (e.g., Siess et al. 2000).

The recent study of massive MS stars in the HD 97950 cluster by Kudryavtseva et al. (2012) finds that the age spread is as small as 0.1 Myr. A few low-mass MS stars at $V > 20$ (within $r > 20''$; right panel in Figure 1) are below the region where most of the cluster MS stars are located (see also Grebel & Gallagher 2004). Considering their small proper motions, these faint MS stars are consistent with being cluster members, which would corroborate an age spread in the cluster as suggested in a number of earlier studies (see Section 1). Alternatively, they might be stars from earlier star formation in the wider NGC 3603 H II region that we observe superimposed at the cluster’s location. That would be consistent with the much more widely distributed population of older PMS stars around the HD 97950 cluster described by Beccari et al. (2010).

Considering the above findings and deliberations, we excluded the MS stars at $V > 20$ from the age determination for the HD 97950 cluster. We conclude that an age spread (if any) in the HD 97950 cluster must be small. We therefore adopt an age of 1 Myr for the cluster.

4. THE MASS FUNCTION AND MASS SEGREGATION

4.1. The Qualitative Approach: Mass Function Determination in Cluster-centric Annuli

In order to derive the mass function of the HD 97950 cluster, we count stars in absolute $V$-magnitude bins spaced such that they cover mass bins with a logarithmic size of 0.2. Using the same procedure as Grebel & Chu (2000), we find the absolute magnitudes corresponding to mass bins along the earlier described isochrones assuming an age of 1 Myr. We applied a color cut of $(V - I) = 2.4$ to separate MS and PMS stars.

Since the crowding is severe in the central region of the HD 97950 cluster, we corrected the count rates for incompleteness depending on their positions and magnitudes. We display the completeness dependence on stellar mass for the PC chip in Figure 2. In the outer annulus ($r > 15''$), stars above $1.5 M_\odot$ are more than 50% complete. As the crowding becomes stronger toward the cluster center, in the region within $r < 5''$ only stars more massive than $4 M_\odot$ are $>50$% complete. Therefore, many faint stars in the central region remain undetected. A completeness test is also run for median and deep exposure images of WFC chips in which crowding effects might intervene. However, since the stars on the WFC chips ($\sim 60''$) are quite far from the cluster core, they are not significantly affected by crowding. Their completeness fraction does not depend on the cluster-centric distance (see Figure 3). The three luminous WR stars near the center of the HD 97950 cluster are saturated in our WFPC2 photometry. Therefore they were added by hand to the highest mass bin using the masses and magnitudes of Schnurr et al. (2008). Since there are very
few MS stars fainter than $V = 20$ mag in the core of the cluster (left panel in Figure 1), the presence of a small number of stars along the lower MS ($V > 20$ mag) at larger cluster-centric distances (right panel in Figure 1) may be attributed to earlier generations (Section 3). Consequently, we exclude stars with $V > 20$ mag and $(V - I) < 2.4$ from our mass function derivation.

Even though the overlap between the WFC chip exposures obtained in 1997 and 2007 is small, we can attempt to increase the area available for analysis by also including those WFC stars in regions that do not overlap. This greatly reduces the corrections for missing area. While this will permit us to consider the mass function within the entire cluster radius ($\sim 60''$; Sung & Bessell 2004), it also requires statistical field star subtraction. This approach is viable for a classical mass function analysis in which we consider the mass function within different cluster-centric annuli, but the subsequent MST analysis is necessarily limited to the inner 20'' covered by the PC chip, since the MST method requires a contiguous area.

We count the total number of incompleteness-corrected, proper-motion-selected foreground stars in the PC and the WFC chips in each magnitude bin considered. Assuming that foreground stars are essentially homogeneously distributed across the entire area covered by the WFPC2 exposures, this approach provides us with the best possible statistics for foreground stars. We obtain the number of foreground stars per magnitude bin and per unit area. In order to correct for field star contamination, we then only need to subtract these numbers after scaling them by the area actually considered within a given annulus.

Fitting the corrected number counts of all probable MS and PMS stars within a mass range of $\sim 1$–$100 M_\odot$ results in a mass function slope of $\Gamma = -0.82 \pm 0.20$ for the PC chip. Our result is in agreement with the earlier WFPC2 study of Sung & Bessell (2004) within error, who obtained $\Gamma = -0.9 \pm 0.1$ for stars on the PC chip. Combining the corrected number counts of all stars within 60'', the resulting slope of the global mass function is $\Gamma = -0.88 \pm 0.15$ (log(mass/$M_\odot$) > 0.6), which is flatter than a Salpeter slope of $-1.35$.

In Figure 4 we also show the mass function of the HD 97950 cluster in different concentric annuli out to 60''. Two effects stand out: (1) the slope of the mass function increases with radius and (2) the more massive stars are concentrated in the center and are missing at larger radii.

Our photometric mass function is affected by the uncertainties in the isochrone models used to derive the masses of cluster member stars. One such uncertainty is the unknown amount of stellar rotation that can affect the colors and magnitudes of stars (Grebek at al. 1996). The stellar evolution models with rotation (Ekström et al. 2012) generate a slightly narrower MS width than non-rotating models (e.g., Schaller et al. 1992), and predict larger final masses at the end of evolution for stars with initial masses in the range of 45–100 $M_\odot$. Thus a flatter slope of mass function will result.

Another uncertainty is unrecognized binarity. Here we implicitly make the simplified assumption that we are dealing with non-rotating, single stars as discussed in Section 3. Also, we neglect a possible age spread in the cluster, but emphasize that a small spread such as the spectroscopically inferred age spread of 1–2 Myr for massive MS stars does not affect the photometrically estimated masses significantly. Moreover, the above analysis of mass segregation in HD 97950 is sensitive to the determination of the position of the cluster center, and the number and size of the radial bins used (e.g., Gouliermis et al. 2004).

4.2. The Quantitative Approach: Mass Segregation Determination Via the Minimum Spanning Tree

In order to quantify the mass segregation, we apply the $\Lambda$ method (Allison et al. 2009b; Parker et al. 2011) to the MS members ($> 3.5 M_\odot$) on the PC chip. We only consider MS stars since lower-mass stars (primarily PMS stars) are incomplete in the center due to crowding effects. We take a subset of $n$ stars of similar mass (the 1st to 6th most massive stars, or the $(n + 1)$th to 2nth most massive stars for example) and find the length of the MST that connects those stars with the shortest path without closed loops. We then take a large number of random sets of $n$ stars of any mass and obtain the median and the 1/6th and 5/6th percentiles to obtain a (possibly asymmetric) 1$\sigma$ error (the vertical bar in Figure 5). A subset is mass segregated if $\Lambda$ (the ratio of the MST length of random stars over massive stars) is larger than unity, i.e., the stars in that subset are more concentrated in their distribution than a random sample (see Allison et al. 2009b; Maschberger & Clarke 2011; Parker et al. 2011).

Figure 5 shows the values of $\Lambda$ for samples of 20 stars moving in steps of 10 stars (therefore every second datapoint is uncorrelated with each other). The first 20 stars all have masses $> 35 M_\odot$, and the second mass bin is in the range 27–45 $M_\odot$. The first two bins have a $\Lambda$ significantly greater than unity—i.e., they are more concentrated than random stars. Varying the size of bins always shows a significant degree of mass segregation for masses $> 30 M_\odot$. Considering error bars,
5. ORIGIN OF THE MASS SEGREGATION

We note that (1) the HD 97950 cluster is strongly mass segregated above $30 \, M_\odot$ and (2) all other masses of stars are randomly distributed throughout the cluster (Figures 4 and 5). As we shall argue, this strongly suggests a dynamical origin for mass segregation in HD 97950. To verify this, we explore the kinematics of the cluster via proper motions. Since the faint stars are incomplete, especially in the cluster center, in order not to bias our result, we only use stars that are more than 50% complete, which corresponds to stars brighter than $V = 18$ mag within the inner 5″ region and stars brighter than $V = 22$ mag in the region $>5''$ from the cluster center.

5.1. Tangential Velocity Profile

We convert the proper motions of stars into tangential velocities and show their distributions in Figure 6. The vertical bar is the tangential velocity dispersion for stars in each magnitude bin or annulus. The (mean) tangential velocity $V_t$ increases slightly from bright to faint stars (upper panel), and from the inner to the outer part of the cluster (lower panel). However, owing to the large scatter, the ascending trend is not significant.

The tangential velocity dispersion for stars $>30 \, M_\odot$ is $6.8 \pm 0.8 \, \text{km s}^{-1}$. It does not change much for stars of $10 \, M_\odot$ ($5.9 \pm 0.6 \, \text{km s}^{-1}$), but increases to $9.0 \pm 0.9 \, \text{km s}^{-1}$ for stars of $\sim 2.5 \, M_\odot$. Since the energy equipartition is mass dependent (see Section 5.3), dynamical segregation may only manifest itself among the few most massive stars, considering the young age of the cluster. This might indicate that equipartition is not taking place in the entire cluster yet (Rochau et al. 2010). However, accounting for the observational uncertainties (see Section 5.2),
the dependence of velocity dispersion on stellar mass is weak, similar to the finding of Rochau et al. (2010).

5.2. Velocity Dispersion

We compute the observed one-dimensional dispersion of proper motions of member stars on the PC chip, which centers at the cluster and provides a more reliable velocity dispersion than the WFC chips due to the higher spatial resolution. We compute the observed one-dimensional dispersion (OD) of the proper motions of member stars: $\sigma_{x,\text{obs}} = 0.316 \pm 0.014$ mas yr$^{-1}$ and $\sigma_{y,\text{obs}} = 0.325 \pm 0.014$ mas yr$^{-1}$ ($x$ and $y$ are pixel coordinates). We assume that the error of the observed dispersion is given by the measurement uncertainty, consisting of random errors from single epoch observations (1997 and 2007) and centroid offsets.

To compute the positional random errors of the observations, we divide the original single epoch data (1997 and 2007) into two subsamples, respectively. After doing photometry on each subsample, we find the common stars ($V < 18$ mag within $5''$ from the cluster center and $V < 22$ mag for regions $>5''$) between the two subsets of the same epoch. The detected positions of the same star in the two subsamples tend to be slightly offset from one another. The standard deviation of this positional offset is the random error, which amounts to $\sigma_{x,r} = 0.262 \pm 0.007$ mas yr$^{-1}$ and $\sigma_{y,r} = 0.233 \pm 0.008$ mas yr$^{-1}$ when considering the contributions from both observing epochs.

We evaluate the quality of the centroids of the detected stars by comparing their positions in images obtained in the same filter and with the same exposure time in the same epoch. The average intra-filter offsets are $\sigma_{x,\text{cent}} \sim 0.10$ mas yr$^{-1}$ and $\sigma_{y,\text{cent}} \sim 0.11$ mas yr$^{-1}$. We subtract the random errors and centroid offsets from the observed dispersion and obtain the absolute one-dimensional velocity dispersions: $\sigma_x = 0.146 \pm 0.016$ mas yr$^{-1}$ and $\sigma_y = 0.198 \pm 0.016$ mas yr$^{-1}$. By adopting a distance of $d = 6.9$ kpc from Sung & Bessell (2004), the one-dimensional velocity dispersions are $\sigma_{x,c} = 4.8 \pm 0.5$ km s$^{-1}$ and $\sigma_{y,c} = 6.5 \pm 0.5$ km s$^{-1}$. The uncertainty, $\sqrt{\text{var}(\sigma_{x/y,c})}$, is computed according to Equation (1) in Pryor & Meylan (1993):

$$\text{var}(\sigma_{x/y,c}) = \left(\sigma_{x/y,c}^2 \right)^2 / (2N\sigma_{x/y,c}^2),$$

where $\sigma_{x/y,c}$ is the real one-dimensional dispersion and $\sigma_{x/y,c}$ the measurement uncertainty (random errors and centroid offsets).

5.3. Dynamical Mass of the Cluster

Harayama et al. (2008) derived the half-mass radius of NGC 3603 to be $R_{\text{hm}} \sim 0.7$ pc from low-mass stars with masses of $\sim 0.5$ to $\sim 2.5 M_\odot$. As stars above $30 M_\odot$ are significantly segregated in the center (Section 4), the true cluster half-mass radius would be smaller. We adopted a half-mass radius of 0.5 pc (Rochau et al. 2010). The dynamical mass $M_{\text{dyn}}$ of the HD 97950 cluster can be calculated from Spitzer’s (1987) formula using the one-dimensional dispersion we derived ($4.8 - 6.5$ km s$^{-1}$)

$$M_{\text{dyn}} \sim \eta \frac{R_{\text{hm}} \sigma_y^2}{G},$$

$\eta$ is a dimensionless parameter in the equation. The square of the three-dimensional velocity dispersion is three times larger than the square of the one-dimensional dispersion, $\sigma_y^2$. Moreover, we are taking a factor of 4/3 from the projection of half-light radius on the sky into account. Furthermore, there is a factor of 5/2 from the conversion to a star cluster fitted with a King mass profile. Thus $\eta$ is about 10.0 (see Fleck et al. 2006 for details). Observers usually use $\eta = 9.75$ when working with the half-mass radius $R_{\text{hm}}$ instead of the half-light radius.

This results in a dynamical mass of $M_{\text{dyn}} \sim 1.9 \pm 0.6 \times 10^4 M_\odot$ ($\eta = 9.75$). This mass is close to the photometric mass $M_{\text{phot}} = 1 - 1.6 \times 10^4 M_\odot$ derived from observations of the stellar content (Harayama et al. 2008), which might suggest NGC 3603 is more or less virialized. Several other young star clusters are also found to be virialized with comparable photometric and dynamical masses, e.g., Westerlund 1, Cottaar et al. (2012); R 136, Bosch et al. (2009); ONC, Jones & Walker (1988), Tobin et al. (2009).

Compared to the previous study of Rochau et al. (2010) of NGC 3603 with the same data set, our study differs from theirs in the following aspects. (1) The velocity dispersion we derived is based on member stars with a completeness of more than 50%. These are stars brighter than $V = 18$ mag within $5''$ from the center and stars brighter than $V = 22$ mag in the annulus $5'' - 20''$. Rochau et al. (2010) computed the velocity dispersion for intermediate-mass stars ($1.7 - 9.0 M_\odot$) in the magnitude range of $16 mag < V < 20$ mag within $15''$. As the photometric uncertainty increases toward fainter stars, this might explain why Rochau et al. (2010) arrived at a smaller value ($4.5 \pm 0.8$ km s$^{-1}$) for the velocity dispersion. (2) The sinusoidal pixel phase error and breathing error on the pixel scale are smaller than the astrometric uncertainty of HSTphot (0.03 pixels). Therefore we did not subtract these two error sources which are considered in Rochau et al. (2010). Nevertheless, the dynamical mass of our study and that of Rochau et al. (2010) ($17,600 \pm 3800 M_\odot$) agree with each other within the errors.

6. DYNAMICAL SEGREGATION IN THE CLUSTER CORE

Very similar patterns of mass segregation have been observed in the two other clusters analyzed with the A method: the ONC (Allison et al. 2009b) and Trumpler 14 (Sana et al. 2010). Allison et al. (2009a) proposed a dynamical origin for mass segregation due to two-body relaxation in a dense phase to explain the ONC. They proposed that the ONC underwent a short-lived dense phase in which the two-body relaxation time was very short.

The two-body relaxation time $t_{\text{relax}}$ of a system is given by

$$t_{\text{relax}} \sim \frac{N}{8 \ln N} t_{\text{cross}},$$

where $N$ is the number of stars in the cluster and $t_{\text{cross}}$ is the crossing time of the system. Dynamical mass segregation occurs due to the equipartition of energies in two-body encounters. The rate at which a star will approach equipartition depends on the mass of that star, $M$, relative to the average mass of stars in the system, $\langle m \rangle$. The time to segregate $t_{\text{seg}}$ down to a mass $M$ is

$$t_{\text{seg}}(M) \sim \frac{\langle m \rangle}{M} t_{\text{relax}} \sim \frac{\langle m \rangle}{M} N M_{\odot} t_{\text{cross}}.$$
the HD 97950 cluster from infrared observations. We adopted their result and assume a total number of stars, $N = 10^4$, and a mean stellar mass of $(m) = 0.4 \, M_\odot$ from Kroupa’s (2002) initial mass function. Inserting $N = 10^4$ and $(m) = 0.4 \, M_\odot$ into Equation (2) suggests that in one crossing time the HD 97950 cluster should mass segregate to a mass of $30 \, M_\odot$. This is exactly what is observed in the core of the cluster. The highest-mass stars are sinking further into the core of the cluster, and are found to be more mass segregated than lower-mass stars (Figure 5). Higher-mass stars are more efficient at this process and thus mass segregate faster. That the stars in the HD 97950 cluster show the same dependence on mass as do purely dynamical and initially non-mass-segregated $N$-body simulations (Allison et al. 2009a, 2010) indicates that dynamical mass segregation may be the dominant process for the mass segregation in the cluster. Furthermore, no formation process (e.g., competitive accretion) is known to produce mass segregation down to one particular mass. Recent infrared observations by Gvaramadze et al. (2012) and Roman-Lopes (2012) find a (bow-shock-producing) massive star and a massive binary in the vicinity of NGC 3603, which are suggested to have been ejected from the cluster HD 97950 via a three-body encounter. These observations may imply that vivid dynamical evolution is already taking place inside the cluster. We also note that binaries may shorten the relaxation time and accelerate segregation. But at the same time, primordial binaries increase the chance of ejections of OB stars (Portegies Zwart et al. 2010), working against the observed mass segregation in the HD 97950 cluster. As no binary sequence can be seen in Figure 1, we cannot quantify the presence of binaries in the cluster and their effects on the mass segregation.  

7. SUMMARY

We analyzed broadband HST/WFPC2 imaging of the HD 97950 star cluster obtained in 1997 and in 2007. We used the epoch difference to establish a proper-motion-selected sample of probable cluster members. The main results of our subsequent analysis are as follows.

1. We find pronounced mass segregation in the cluster, as did previous studies. The slope of the mass function, measured within concentric annuli around the cluster center, varies radially from $-0.26 \pm 0.32$ within $S'$ from the center to $-0.94 \pm 0.36$ in an annulus of $40''-60''$ around the center. Very massive stars are only found near the cluster center and are not observed at larger radii. The global slope of the mass function for member stars on the PC chip is $\Gamma = -0.82 \pm 0.20$. It stays almost unchanged at a value of $\Gamma = -0.88 \pm 0.15$ for all stars (log(mass/$M_\odot$) > 6) within the cluster radius of $\sim 60''$ (Sung & Bessell 2004), which is flatter than a Salpeter slope.

2. Using the MST method, we find the HD 97950 cluster to be significantly mass segregated down to $30 \, M_\odot$. The most massive stars are the most mass-segregated ones. A simple extension of the Allison et al. (2009a) dynamical model for mass segregation in the ONC suggests that HD 97950 should be mass segregated to $30 \, M_\odot$, in very good agreement with the observations. Furthermore, we find a weak dependence of the tangential velocity dispersion on the stellar mass. The tangential velocity dispersion increases from $6.8 \pm 0.8 \, \text{km s}^{-1}$ for stars $>30 \, M_\odot$ to $9.0 \pm 0.9 \, \text{km s}^{-1}$ for stars of $\sim 2.5 \, M_\odot$. Considering the uncertainty, this suggests that energy equipartition does not affect the whole cluster yet, but so far only the most massive stars of the HD 97950 cluster.

3. We compute a dynamical mass of $M_{\text{dyn}} \sim (1.9 \pm 0.6) \times 10^4 \, M_\odot$ for the HD 97950 cluster in NGC 3603, which is close to its photometric mass (Harayama et al. 2008). This may imply that the cluster is in a state of virialization, similar to other young massive clusters.

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