THE LOW-MASS INITIAL MASS FUNCTION IN THE 30 DORADUS STARBURST CLUSTER

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Received 2009 January 7; accepted 2009 October 30; published 2009 December 4

ABSTRACT

We present deep Hubble Space Telescope NICMOS 2 F160W band observations of the central 56′′ × 57′′ (14 pc × 14.25 pc) region around R136 in the starburst cluster 30 Dor (NGC 2070) located in the Large Magellanic Cloud. Our aim is to derive the stellar initial mass function (IMF) down to ~1 $M_{\odot}$ in order to test whether the IMF in a massive metal-poor cluster is similar to that observed in nearby young clusters and the field in our Galaxy. We estimate the mean age of the cluster to be 3 Myr by combining our F160W photometry with previously obtained HST WFPC2 optical F555W and F814W band photometry and comparing the stellar locus in the color–magnitude diagram with main sequence and pre-main sequence isochrones. The color–magnitude diagrams show the presence of differential extinction and possibly an age spread of a few megayear. We convert the magnitudes into masses adopting both a constant isochrone and a constant star formation history from 2 to 4 Myr. We derive the IMF after correcting for incompleteness due to crowding. The faintest stars detected have a mass of 0.5 $M_{\odot}$ and the data are more than 50% complete outside a radius of 5 pc down to a mass limit of 1.1 $M_{\odot}$ for 3 Myr old objects. We find an IMF of $\frac{dN}{d\log M} \propto M^{-1.2 \pm 0.2}$ over the mass range 1.1–20 $M_{\odot}$ only slightly shallower than a Salpeter IMF. In particular, we find no strong evidence for a flattening of the IMF down to 1.1 $M_{\odot}$ at a distance of 5 pc from the center, in contrast to a flattening at 2 $M_{\odot}$ at a radius of 2 pc, reported in a previous optical HST study. We examine several possible reasons for the different results including the possible presence of mass segregation and the effects of differential extinction, particularly for the pre-main sequence sources. If the IMF determined here applies to the whole cluster, the cluster would be massive enough to remain bound and evolve into a relatively low-mass globular cluster.

Key words: globular clusters: individual (30 Doradus) – stars: formation – stars: luminosity function, mass function – stars: pre-main sequence

Online-only material: machine readable table

1. INTRODUCTION

The shape of the stellar initial mass function (IMF) and whether it is universal or not are key issues in astrophysics. For clusters within 2 kpc, there is no compelling evidence for variations in the stellar IMF (e.g., Meyer et al. 2000; Kroupa 2002; Chabrier 2005) or the brown dwarf IMF (e.g., Andersen et al. 2008). However, these clusters only span a limited range in total cluster mass (10$^2$–10$^3$ $M_{\odot}$) and all have a metallicity similar to the solar value. Thus, we are forced to observe more extreme regions of star formation in search of variations in the IMF as a function of environment. It has been suggested that the shape of the IMF and in particular the characteristic mass where the IMF flattens from a Salpeter power-law could depend on the metallicity in the molecular cloud out of which the stars are formed. Low & Lynden-Bell (1976), Larson (1998), and Omukai (2000) suggested that a lower metallicity results in higher temperatures in the molecular cloud which would increase the Jeans mass. This would in turn result in a top heavy IMF relative to the solar metallicity IMF.

The closest place with massive metal-poor young star clusters is the Large Magellanic Cloud (LMC). The metallicity is only $\frac{1}{3}$ - $\frac{1}{4}$ the solar value (Smith 1999) and star clusters can be studied in some detail despite a distance of ~50 kpc (Westerlund 1997). Of particular interest is the 30 Dor cluster which is powering the most luminous H II region in the Local Group (Kennicutt 1984). The cluster has a mass of at least 2.2 × 10$^4$ $M_{\odot}$ within a radius of 4.7 pc (Hunter et al. 1995) and is a relatively low-mass analog to the more distant starburst clusters. R136 lies at the center of the 30 Dor cluster and has long commanded significant attention: once thought to be a single ~1000 $M_{\odot}$ star (Cassinelli et al. 1981), the region is now known to host numerous O stars (Melnick 1985; Weigelt & Baier 1985; Pehlemann et al. 1992; Campbell et al. 1992).

The whole 30 Dor region, with a size of 200 pc, appears to have an age spread of ~20 Myr (McGregor & Hyland 1981; Selman et al. 1999) with stars still forming (Rubio et al. 1992; Maercker & Burton 2005). R136 appears to have a much smaller average age spread of at most a few megayears (Melnick 1985; Brandl et al. 1996; Massey & Hunter 1998). An age of 2 Myr or less is inferred from spectroscopy of the O stars in the very cluster center (Massey & Hunter 1998), whereas the intermediate mass population is thought to be ~3–4 Myr old (Hunter et al. 1995). Massey & Hunter (1998) obtained Hubble Space Telescope (HST) spectroscopy of the 65 bluest and most luminous sources within 17′′ of the cluster center. They derived the IMF over the mass range 15–120 $M_{\odot}$ and found it to be well approximated by a power-law $\frac{dN}{d\log M} \propto M^\Gamma$ with a slope of $\Gamma = -1.3 \pm 0.1$, ...
consistent with a Salpeter slope IMF (Salpeter 1955). Hunter et al. (1995, 1996) obtained F555W (V) and F814W (i) band optical photometry utilizing HST/WFPC2 in order to resolve the cluster’s intermediate mass stellar population. The IMF derived for different annuli out to a radius of 4.7 pc was found to be in the range \(-1.46 < \Gamma < -1.17\) for the mass range 2.8–15 $M_\odot$, again consistent with a Salpeter slope IMF. Massey & Hunter (1998) combined their results for the high-mass IMF with the results from Hunter et al. (1995, 1996) in order to constrain the IMF from 2.8 $M_\odot$ up to 120 $M_\odot$. Comparing the number of high-mass stars predicted by the intermediate-mass IMF from Hunter et al. (1996), they found the number of massive stars was consistent with a single power-law IMF with a Salpeter slope, i.e., $\Gamma = -1.35$.

Combining the two data sets used in Hunter et al. (1995, 1996), Sirianni et al. (2000) derived the IMF between 1.35 $M_\odot$ and 6.5 $M_\odot$, extending the IMF determination into the mass range where the stars are still in their pre-main sequence phase. The IMF was derived in a box with the dimensions $\sim 30'4'' \times 26'8''$ (7.6 pc $\times$ 6.7 pc), but excluding the inner most 13'6'' $\times$ 8'6'' (3.5 pc $\times$ 2.2 pc). Again, a Salpeter slope was found down to 2 $M_\odot$, but the IMF was found to be flatter than Salpeter, $\Gamma = -0.27 \pm 0.08$, between 1.35 $M_\odot$ and 2 $M_\odot$, suggesting the characteristic mass is higher in this massive, metal-poor cluster than $\sim 0.5 M_\odot$ as found in the Galactic field (Kroupa 2002).

The foreground ($A_V = 0.7$ mag) and differential extinction ($A_V \sim 0 - 2$ mag) within the cluster (Brandl et al. 1996) make it desirable to observe the cluster in the infrared, for example, the $H$ band where the extinction is less than 20% that of the $V$ band. In addition, pre-main sequence stars are often associated with circumstellar disks and outflows which will introduce additional extinction for the clusters low-mass content.

We have observed R136 with HST/NICMOS Camera 2 through the $F160W$ band, which is similar to a ground-based $H$ filter. The observations were aimed at being sensitive to objects below 1 $M_\odot$ for a stellar population with an age of 3 Myr. Preliminary results have previously been presented in Zinnecker et al. (1999, 2002), and Andersen et al. (2005).

The paper is structured as follows. The data and their reduction are described in Section 2. Section 3 shows the results for the $F160W$ band imaging. The IMF is derived in Section 4 and compared with the IMF derived by Sirianni et al. (2000). We point out several plausible reasons for the different results in the optical and near-infrared, including mass segregation, and differential extinction. Finally, our conclusions are presented in Section 5.

2. DATA REDUCTION AND PHOTOMETRY

2.1. Observations

We have obtained HST/NICMOS Camera 2 images through the $F160W$ band of the central $56'' \times 57''$ region around R136 in the 30 Dor cluster (HST program ID 7370). The observations were centered on the cluster (R.A., decl.) = (05:38:43.3, –69:06:08) and on two adjacent control fields centered on (05:38:42.4,–68:52:00), and (05:38:56.9,–68:52:00). The observing dates were 1997 October 14 and 16. The field of view of the 256 $\times$ 256 pixel NICMOS Camera 2 is $19'' \times 19''$ with a pixel scale of 0.075”, resulting in Nyquist sampling of diffraction-limited $F160W$ band data. Each position in a $3 \times 3$ mosaic centered on R136 was observed 4 times with small dithers of $\sim 16$ pixels. The data were obtained in non-destructive MULTI-ACCUM mode such that the photometry of the bright stars can be retrieved due to the first short integration in each exposure. The integration time for each dither position was 896 s, resulting in a total integration time of 3584 s for each position in the mosaic. The two control fields were observed in a similar manner.

The location of the mosaic is shown in Figure 1 and the NICMOS mosaic is shown in Figure 2. The faintest stars visible with the stretch used here have an $F160W$ magnitude of $\sim 21.5$ mag, corresponding to a mass of 0.8 $M_\odot$, based on the pre-main sequence models of Siess et al. (2000), adopting an age of 3 Myr (Hunter et al. 1995), half solar metallicity, and an extinction of $A_V = 1.85$ mag (see Section 3.2). For comparison, the similar detection limit in an uncrowded environment without nebulosity would be $\sim 23.5$ mag according to the NICMOS exposure time calculator.

2.2. Data Reduction

Each individual image was processed through the calnica and calnicb pipelines as well as the biasseq and pedsky procedures within the IRAF environment. The tasks are described in detail in the NICMOS Data Handbook. We used synthetic dark frames and flat fields created for the appropriate instrument temperature at each exposure. The biasseq task corrects differences in bias levels for each chip between different sub-exposures. The pedsky task corrects differences in the bias level for each quadrant of the chip when the array is reset before the exposure. The data for each position in the mosaic were combined using the drizzle task. The reduced pixel size (0.0375”) was chosen as half the detector pixel size. Bad pixels, bad columns, and the coronagraphic hole were flagged as bad pixels before the images were combined.
TINYTIM software (Hook & Krist 1997) was used to create the PSF and the spatial variability of the PSF. Instead, the PSF was obtained from the data due to the high degree of source crowding. Utilizing point-spread function (PSF) photometry was performed via point-spread function (PSF) photometry (daofind, allstar) in each frame and used allstar to remove these detections together with other false detections through the visual inspection of all sources. We have further utilized the artificial sources as a function of the location on the array. The source detection and photometry was performed on each individual position in the mosaic due to the linearly varying PSF. The artificial stars followed a synthetic PSF. TINYTIM allows to create a PSF that varies as a function of the location on the array. The artificial stars were located at the diffraction spikes and spots from bright stars. The two star lists (the brightest stars and the fainter stars) were joined into one and these stars were removed from the original frame, again using allstar. Fainter stars are then found from the frame with the already detected stars removed. This process was iterated until stars at 10σ peak pixel intensity over the background were detected and removed. The frame with the stars removed was then ring-median filtered to remove stellar residuals but to retain the large-scale nebulosity in each frame. The median-filtered image was then removed from the original frame and the star detection process was repeated in this frame but now continued to a detection threshold of 5σ. A 5σ instead of, e.g., a 3σ threshold was selected to limit the risks of false detections due to noise spikes. We finally made sure by visual inspection that every detection indeed was a point source and that it was not a spurious detection due to the diffraction spikes and spots from bright stars.

The main interest here is in the low-mass (faint) stellar content in R136 and one concern is the detection of residuals from the bright stars as false stellar objects. Some false sources were detected by daofind but are rejected during the PSF fitting routine. A few remained from the brightest stars. They typically produced at most a few false detections in the diffraction spikes that were ∼6–7 mag fainter than the bright source. We removed these detections together with other false detection through the visual inspection of all sources. We have further utilized the artificial star experiments described below to examine how many detections are false due to the residuals from bright stars. We had only false positives associated with the brightest artificial stars (F160W < 12 mag). For artificial stars fainter than F160W ~14 mag, no false detections were present. The false detections for the bright stars were located at the diffraction spikes and would have been identified in the manual inspection of the source list.

We found a total of 10,108 uniquely detected sources with a formal error smaller than 0.1 mag and brighter than F160W = 22.5 mag in the nine frames. Below this magnitude limit the incompleteness is substantial, as discussed below. Table 1 presents the list of detected stars.

### 2.3. Source Detection and Photometry

Source detection was done using daofind and photometry was performed via point-spread function (PSF) photometry utilizing allstar within the IRAF environment. It was difficult to obtain a good PSF model from the data due to the high degree of crowding and the spatial variability of the PSF. Instead, the TINYTIM PSF was created for five different positions on the NICMOS Camera 2 array and the PSFs were placed in an empty frame with the same number of pixels as the NICMOS Camera 2 array. Four frames were created with offsets between each PSF identical to the offsets used for the science data in order to replicate the data as closely as possible. The four PSF frames were then combined using drizzle together in the same manner as the science data and a linearly varying PSF was created from the drizzled frame.

Source detection is complicated due to the diffraction features present in NICMOS data. Adoption of a low threshold for source detection led to numerous diffraction spots from bright stars being erroneously identified as fainter stars. Instead the source detection was done in the following way in order to limit false detections. We first detected the brightest stars (brighter than 1000σ) in each frame and used allstar to remove these detections. A search for fainter stars (brighter than 500σ) was then performed in the frame with the bright stars removed. Since the removal of the brightest stars also removed the diffraction pattern associated with them, we did not detect the diffraction spots as stars. The two star lists (the brightest stars and the fainter stars) were joined into one and these stars were removed from the original frame, again using allstar. Fainter stars are then found from the frame with the already detected stars removed. This process was iterated until stars at 10σ peak pixel intensity over the background were detected and removed. The frame with the stars removed was then ring-median filtered to remove stellar residuals but to retain the large-scale nebulosity in each frame. The median-filtered image was then removed from the original frame and the star detection process was repeated in this frame but now continued to a detection threshold of 5σ. A 5σ instead of, e.g., a 3σ threshold was selected to limit the risks of false detections due to noise spikes. We finally made sure by visual inspection that every detection indeed was a point source and that it was not a spurious detection due to the diffraction spikes and spots from bright stars.

Table 1 The F160W Band Detected Sources in R 136

| Xcen | Ycen | F160W | F160W err |
|------|------|-------|----------|
| 104.546 | 280.899 | 19.09 | 0.04 |
| 156.263 | 148.125 | 20.28 | 0.05 |
| 121.580 | 148.709 | 20.15 | 0.03 |
| 315.194 | 150.819 | 20.29 | 0.03 |
| 481.127 | 152.319 | 20.27 | 0.04 |
| 69.890 | 154.680 | 17.73 | 0.05 |
| 280.115 | 155.118 | 19.76 | 0.01 |
| 91.993 | 157.119 | 18.87 | 0.04 |
| 443.582 | 157.392 | 17.34 | 0.02 |

(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.)

The effects of crowding were examined by placing artificial stars in the individual frames using the PSF created from the synthetic TINYTIM PSF. The artificial stars followed a

2.4. Completeness Corrections

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luminosity function (LF) with a similar slope to that of the observed stars (see Section 3) but with a surface density 10% that of the detected number of stars to avoid affecting the crowding characteristics of the real stars. We performed 100 artificial star experiments for each frame, for a total of 10 times more artificial stars than real stars. Figure 3 shows the resulting recovery fractions as a function of the input magnitudes for several annuli around the cluster center. The difference of the size of the error bars as a function of distance from the cluster center is due to a lower number of artificial stars placed in the central parts of the cluster. This is a consequence of adding 10% artificial stars relative to observed stars in each artificial star experiment and the relative number of stars in each annulus. The IMF is not determined in regions with this low completeness. We are mainly interested in the low-mass stellar content of the cluster, which is below the 50% completeness in the central parts. The uncertainty in the completeness corrections for the inner parts of the cluster will therefore not affect the conclusions drawn for the stellar populations further out.

The completeness is a strong function of the radial distance from the center. For the outer regions of the cluster, 50% or more of the stars brighter than $F160W = 21.5$ mag are detected, whereas only the very brightest stars are detected in the innermost region. In an annulus at 0.6–1 pc radius from the center, we detect 50% or more of the stars brighter than $F160W = 18.0$ mag. Adopting the PMS models of Siess et al. (2000) and the main sequence models of Marigo et al. (2008), $F160W = 21.5$ mag corresponds to a 0.8 $M_\odot$, half solar metallicity, 3 Myr old object, whereas $F160W = 18$ mag corresponds to a 7.5 $M_\odot$ star, assuming an extinction of $A_V = 1.85$ mag in both cases.

### 2.5. Photometric Accuracy

We have investigated the accuracy of the derived photometry by using the stars detected in the overlap regions of several fields. Figure 4 shows the difference in derived magnitude for stars detected in the overlap regions of the mosaic. Dots denote stars outside a 2 pc radius and plus signs denote stars between 1.25 and 2 pc radius, respectively.

The $F160W$ band photometry has been compared with the ground-based $H$-band photometry obtained using adaptive optics observations by Brandl et al. (1996). Figure 4 shows the magnitude difference between the adaptive optics photometry and this study based on 829 stars common to both data sets. Stars were considered detected in both data sets if the spatial position coincided within 2.5 drizzled pixels, corresponding to 0.094 arcsec. Some scatter is present between the two data sets, especially for the fainter stars. However, the median difference between the magnitudes derived for the two data sets is less than 6% for objects $F160W < 18$ mag. We have in the following treated the $F160W$ observations as a standard Cousins $H$ band.

Conversely, there appears to be a tendency for the fainter stars to be brighter in the $F160W$ data than in the $H$-band data of Brandl et al. (1996). The tendency for the fainter stars to be skewed toward fainter $H$-band magnitudes is an effect also seen in other comparisons between HST/NICMOS and AO data (e.g., Stolte et al. 2002) who suggest it is due to the extended halos present in AO observations around bright stars.

### 3. RESULTS

The immediate results from the $F160W$ band HST photometry are presented. After discussing the LF for different annuli, the luminosity profile for the cluster is derived. The $F160W$ band data are combined with the optical $HST$ data by Hunter et al. (1995) and the color–magnitude diagrams are presented. Utilizing the two color–magnitude diagrams we show that the spread observed for the higher mass stars is consistent with that expected due to reddening. We estimate the average age for the stellar population and discuss the possible presence of an age spread.
Figure 4. Left: comparison of the NICMOS 2 photometry derived in this study with the ground-based AO H-band observations by Brandl et al. (1996). The mean difference between the two data sets for objects with $F160W \leq 17$ mag is 0.03 mag, and the standard deviation is 0.2 mag. Right: the magnitude difference for sources detected in two different images in the mosaic. A star was identified in both images if its position was within one pixel. Plus signs denote stars within a 2 pc radius of the center, but outside 1.25 pc; the dots denote stars outside this annulus. The rms in the error for objects with $F160W < 21.5$ mag, which is the 50% completeness limit in the outskirts of the cluster, is 0.17 mag.

Table 2
The Derived Slopes of the $F160W$ Band LFs for R136 Together with Their Uncertainties

| Annulus (pc) | Slope ($\alpha$) | Max ($F160W$) |
|-------------|------------------|---------------|
| 0.6–1.0     | 0.38 ± 0.07      | 18.0          |
| 1.0–2.0     | 0.32 ± 0.03      | 19.5          |
| 2.0–3.5     | 0.31 ± 0.02      | 20.5          |
| 3.5–5.0     | 0.32 ± 0.01      | 21.0          |
| 5.0–7.0     | 0.31 ± 0.01      | 21.5          |

Notes. The inner and outer radii are given for each annulus. The maximum $F160W$ band magnitude (50% completeness limit) used to derive the fit is shown as well.

$\frac{dN}{dF_{160W}} \propto 10^{\alpha F_{160W}}$.

3.1. Luminosity Functions

The star counts in the central 0.6 pc radius region are heavily affected by low number statistics, crowding even for the brightest stars, and relatively uncertain incompleteness corrections. We therefore focus on the sources outside 0.6 pc in this paper. Figure 5 shows the $F160W$ band LFs for the 0.6–7 pc radius region of the 30 Dor cluster divided into several radial bins to show the difference in photometric depth due to crowding. Overplotted are the completeness-corrected LFs, where each bin has been divided by the corresponding recovery fraction from the artificial star experiments.

The completeness–corrected LFs are relatively smooth and have been fitted with power laws down to the 50% completeness limit. The derived slopes with their 1σ uncertainties and the 50% completeness limits are presented in Table 2. Although the slope in the inner annulus is found to be more shallow, the derived slopes are consistent with each other within 2σ with an average slope of 0.31 and the shallow slope is not significant.

The completeness-corrected combined histogram for the stars detected in the two off–cluster control fields is shown in the lower right panel in Figure 5. From the histogram, it can be seen that the field star contamination found from the star counts is ≈10%–15% for the faintest stars in the 5–7 pc annulus and less closer to the center as well as for brighter stars. Although the contamination of field stars is found to be relatively small it is not negligible and they are therefore statistically subtracted from the cluster population in the following analysis (Section 4).

Figure 5. $F160W$ band LFs for different annuli in R136 outside a radius of 0.6 pc. Solid histograms indicate the observed number of stars per magnitude bin while the completeness-corrected data are shown as the dotted lined histograms. The error bars include the Poisson errors and the uncertainty from the incompleteness calculations where the two error terms have been added in the quadrature. In each panel, an arrow indicates the bin where the completeness correction is 50%. The solid straight line is a weighted fit to the completeness corrected histograms down to the 50% completeness limit. The lower right panel shows the completeness corrected average LF for the two control fields (solid histogram) associated with the 30 Dor cluster. The completeness corrected LF for the 5–7 pc annulus in 30 Dor is shown as the dashed histogram for comparison.

3.2. The Optical–Near-infrared Color–Magnitude Diagrams

Next, the $F160W$ band photometry is combined with the optical data presented by Hunter et al. (1995). A star was
considered detected in both surveys if the spatial position agreed within 2.5 drizzled NICMOS Camera 2 pixels (0.094). In the cases where two optical stars were located within the search radius of the star detected in the NICMOS Camera 2 observations, the brightest star was chosen as the match.

We find in total 2680 in common with the Hunter et al. (1995) survey that detected 3623 stars the inner 35″ of the cluster. 1848 of those sources have a combined formal photometric error in the $F555W$–$F160W$ color of less than 0.1 mag. Within the area covered by Hunter et al. (1995) we detect a total of 5095 sources. Most of the stars detected by the NICMOS survey but not the WFPC2 observations are fainter than $F160W = 20$ mag. Assuming an object age of 3 Myr and an average extinction of $A_V = 1.85$ mag (see below), the similar object would have a magnitude in the $F814W$ band of $\sim 22$ mag. For objects with more extinction, they will be even harder to detect in the $F814W$ band. Hunter et al. (1995) essentially do not detect any stars within a 1 pc radius at this magnitude or fainter. Only 1 in 4 stars in the magnitude interval $F814W = 21$–$22$ mag was detected outside 1 pc. It is thus not surprising that a significant population of faint stars are detected in the NICMOS survey relative to the WFPC2 survey. Nevertheless, the lower spatial resolution of the NICMOS observations results in a low recovery fraction at these magnitudes in the central few pc of the cluster.

The majority of the sources not detected in the NICMOS survey but at optical wavelengths are located within a radius of 1 pc. The lack of detection is due to the lower spatial resolution in this study relative to the optical HST data. The resolution is almost a factor of 2 better in the $F814W$ band than in the $F160W$ band. Sources not detected in the NICMOS data outside 1 pc are mainly due to crowding as well. Indeed, visual inspection of the location of the stars detected in the optical but not near-infrared shows that they are often located either very close to the core or on the first Airy ring of a bright source.

The $F555W$–$F160W$ versus $F160W$ color–magnitude diagram is shown in Figure 6. Overplotted are a 3 Myr isochrone from Marigo et al. (2008) below $7 M_\odot$. The stars above $7 M_\odot$ are all expected to be on the main sequence. Both isochrones on the first Airy ring of a bright source.

We have forced the Marigo et al. (2008) isochrone to match the cluster. 1848 stars were calculated adopting a metallicity of half the solar value, and the 3 Myr isochrone above $7 M_\odot$. The stars above $7 M_\odot$ and up to the maximum mass we fit the IMF in Section 4.1 ($20 M_\odot$) are all expected to be on the main sequence. Both isochrones are calculated adopting a metallicity of half the solar value, typical for the LMC (Smith 1999). The two isochrones have a small offset in both the $V$ (0.06 mag) and $H$ (0.07 mag) bands. We have forced the Marigo et al. (2008) isochrone to match the Siess et al. (2000) isochrone at $7 M_\odot$.

It is evident that there is a significant scatter in the color–magnitude diagram. The scatter is likely due to a combination of binary systems (both physical and chance alignments), differential extinction, photometric errors, and a possible age spread. The median extinction is found for the main sequence part of the isochrone. For objects in the range $7$–$20 M_\odot$, we find...
a median extinction of $A_V = 1.85$ mag which is slightly higher than the reddening found by Selman et al. (1999) in the inner part of the 30 Dor region.

At masses below $7 M_\odot$, the spread in the color–magnitude diagram is larger but almost exclusively extends to the red part of the diagram. This indicates the lower mass objects on average have an excess amount of extinction relative to the higher mass objects. Selman et al. (1999) observed stars more massive than 10 $M_\odot$ and would not detect the additional reddening for the lower mass sources. The possible sources for the additional reddening is described in Section 3.3.

We have estimated an average age for the cluster by utilizing the fact the isochrone is almost horizontal in the color range $F555W–F160W = 1.5–2.5$ mag and around $F160W \sim 19$ mag. The median $F160W$ magnitude is 19.0 mag in this region of the color–magnitude diagram. Adopting an average extinction of $A_V = 1.85$ mag, this corresponds to the $F160W$ magnitudes of the 3 Myr isochrone in the same color range. We have thus adopted 3 Myr as the mean age of the low mass cluster population and a 3 Myr isochrone is adopted to create a mass–luminosity relation in order to turn the luminosities into masses for objects below 7 $M_\odot$ and the 3 Myr Marigo et al. (2008) isochrone above. We will in Section 4 discuss the effects on the derived IMF when an age spread of 2 Myr is adopted.

The right-hand panel in Figure 6 shows the $I$–$F160W$ versus $F160W$ color–magnitude diagram. It is evident that the clustering around the isochrone is tighter than for the $V$–$F160W$ versus $F160W$ color–magnitude diagram. This is expected if a large part of the scatter is due to differential extinction. We can calculate the scatter around the main sequence in both color–magnitude diagrams and compare with the difference predicted from extinction.

If the spread in the color–magnitude diagrams is due to extinction we expect the ratio of spread in the $V$–$F160W$ versus $F160W$ diagram to be the ratio of the extinction in each color, i.e., $(1 - 0.192)/(0.62 - 0.192) = 1.88$ times larger than in the $I$–$F160W$ versus $F160W$ color–magnitude diagram. Since the isochrone is almost vertical in both diagrams, we have calculated the standard deviation around the reddened isochrone in both color–magnitude diagrams. We have used the stars with good photometry, better than 5% in each filter, and in the magnitude range 13 mag < $F160W$ < 17 mag. The standard deviation found for the $V$–$F160W$ and $I$–$F160W$ color–magnitude diagrams are 0.60 mag, and 0.36 mag and the ratio is 1.7. If the measurement errors are taken into account this ratio increases. The typical errors for the culled sample are 0.04, 0.02, and 0.03 mag for the $V$, $I$, and $F160W$ bands, respectively. After taking the measurement errors into account, the ratio is found to be 1.9, assuming the measurement errors in two filters are independent. Due to blending, this is not necessarily the case. Thus, 1.9 is an upper limit and we thus find the ratio to be between 1.7 and 1.9, in agreement with the scatter being due to differential extinction.

Since the amount of differential extinction does not affect the $F160W$ band photometry significantly, the single band photometry presented here is competitive with the 2-band optical photometry. There is a unique translation from the $F160W$ band magnitude to the object mass for the majority of the mass range. For the optical photometry, the color information is used to determine the extinction and the mass function is thus effectively determined by the de-reddened $V$-band magnitude.

### 3.3. The Differences Between the Optical and Near-infrared HST Observations

The main advantage of the optical relative to the near-infrared HST photometry is the improved resolution due to the smaller diffraction limit. The stellar content can therefore be resolved to lower masses closer to the cluster core than is possible with the near-infrared observations. However, phenomena associated with the star formation process can introduce additional reddening that can complicate the derivation of the low-mass IMF from optical data. The low-mass objects may still be associated with a circumstellar disk. There is evidence from, e.g., the Orion Nebula Cluster that circumstellar disks can survive the UV radiation from massive stars (Robberto et al. 2004). Even if the disks are being evaporated by the radiation field from the early-type stars, the evaporated material will be a further source of reddening. Patchy extinction associated with the 30 Dor complex and located in the foreground of R 136 will be an additional source of differential reddening. There are signs in the optical images presented in Figure 1 of Sirianni et al. (2000) of patches of extinction, e.g., to the east–north–east of the cluster center. If variable extinction is present or if a significant fraction of the stars are associated with disks or outflows, an extinction limited sample has to be created in order to avoid biases against detection of the low-mass stars.

The near-infrared photometry is affected by differential extinction as well but the effect is less than 20% of that measured in the $V$ band. Thus, whereas the IMF derived from optical observations where an extinction limited sample is not defined might be severely affected for the low-mass objects, the effect on near-infrared observations is modest. Therefore, in the outer parts of the cluster where crowding is a smaller issue than closer to the center, the near-infrared observations are more suitable to detect and characterize the low-mass stellar population in the cluster.

On the other hand, single-band photometry has the disadvantage that there is no information on the age of individual objects. We investigate in the following section how this might affect the derived IMF. We note that if differential extinction is present, the situation is no better for the optical photometry. Even though the cluster was observed through two filters in the optical, there is still a degeneracy between age and extinction. Sirianni et al. (2000) converted the $V$–$I$ photometry into an effective temperature and used that effective temperature to obtain a bolometric correction. Without de-reddening the sources, the age of a cluster member can be in error and hence the mass estimates will be uncertain.

### 4. ANALYSIS

We construct a mass–luminosity relation by combining the main sequence models by Marigo et al. (2008), and the pre-main sequence models of Siess et al. (2000) in order to infer the stellar mass from the $F160W$ band magnitude. We then derive the mass functions for R136 outside 0.6 pc where the 50% completeness limit corresponds to a stellar mass below 10 $M_\odot$. Deriving the IMF this way is a well-established procedure (Lada & Lada 2003; Muench et al. 2002). We further discuss the potential effect of extinction on the derived IMF. Finally, we search for evidence for mass segregation in the outer parts of the cluster using the cumulative LFs.

#### 4.1. Deriving the Mass Function

A mass–luminosity relation is needed to convert the derived $F160W$ band magnitude for each star to a mass. We use the Siess...
et al. (2000) isochrones for stars below 7 \( M_\odot \) and the Marigo et al. (2008) 3 Myr isochrone for the more massive stars as discussed in Section 3.2. The age of the cluster is first assumed to be 3 Myr and is later varied to examine the effects on the derived IMF for different cluster ages. Stars below \( \sim 3 \ M_\odot \) are on the pre-main sequence isochrone, whereas the more massive stars up to our upper mass limit of 20 \( M_\odot \) (see below) are on the main sequence. The adopted mass–luminosity relation is shown in Figure 7.

We have limited knowledge of the extinction for the majority of our objects. Instead, we have adopted an average extinction of \( A_V = 1.85 \) mag, as determined from the \( V-H \) versus \( H \) color–magnitude diagram in Figure 6. Since the amount of extinction ranges between \( A_V = 0.7-3 \) mag (Brandl et al. 1996) the extinction for an individual object might be wrong by up to \( A_V \sim 1 \) mag, a maximum error \( < 0.2 \) mag in the \( F160W \) band. This corresponds to an error of \( \sim 10\% \) when the luminosity is transformed into a mass.

Figure 8 shows the derived mass functions outside 0.6 pc for a 3 Myr isochrone after field stars have been subtracted statistically in each annulus. The mass functions are in general smooth and well fit by power laws. However, there appears to be some structure in the derived IMFs at intermediate masses, 2–4 \( M_\odot \), which is the region where the pre-main sequence track joins the main sequence. The mass–luminosity relation is plagued by a non-monotonous feature at this mass range (see Figure 7), which marks the radiative-convective gap (Mayne et al. 2007) and the transition region from pre-main sequence to main sequence (see also Stolte et al. 2004). A similar structure in the derived IMF is seen in the results from, e.g., NGC 3603 but at a slightly higher mass since the cluster is younger (e.g., Stolte et al. 2006). The turn-on mass is higher for a younger cluster. Thus, we would expect the kink in the mass–luminosity relation to move to higher masses for a younger cluster. Since this is what is seen comparing NGC 3603 and R 136, it indicates indeed a feature of the isochrones and not a feature intrinsic to the cluster. The number of stars in each mass bin is provided in Table 3.

Power laws have been fitted to each of the histograms in order to derive the slopes of the mass function in each annulus. The fit was done over the mass range from 20 \( M_\odot \) down to the 50\% completeness limit for each annulus. The mass for stars above \( \sim 20 \ M_\odot \) is very poorly constrained from near-infrared observations due to uncertainties in the bolometric corrections (e.g., Massey 2003). The derived slopes \( \Gamma \), where \( dN/d\log M \propto M^\Gamma \), are indicated in Figure 8 and are also presented in Table 4. The derived slopes for annuli outside 1 pc are consistent with each other within 2\( \sigma \) error bars. For the 3–5 pc and 5–7 pc annuli where the data are complete to below 2 \( M_\odot \), the slopes are found to be \( -1.2 \pm 0.1 \) and \( -0.9 \pm 0.2 \), respectively, slightly shallower than the slope of \( \Gamma = -1.28 \pm 0.05 \) derived by Sirianni et al. (2000) above 2 \( M_\odot \), except that in our case the IMF continues as a power law down to 0.8 \( M_\odot \).

Has the fact that we used the whole mass range for our power-law fit washed out a possible flattening at the low mass end? To test this possibility, we have additionally fitted a separate power law to the low-mass part of the IMF. Only the part of the mass function that is not influenced by the kink in the mass–luminosity relation is used. This region is limited to masses below 1.7 \( M_\odot \) for the 3 Myr isochrone. It is therefore only for the 5–7 pc annulus that a reasonable mass range is covered to fit the IMF. We find the slope to be \( \Gamma = -0.9 \pm 0.2 \), which is more shallow but consistent at the 2\( \sigma \) level with a Salpeter IMF and is consistent with the slope derived for the full mass range.

We have derived the IMF in the same boxes as done by Sirianni et al. (2000). The completeness correction was calculated independently for each box before the IMFs were combined to the average IMF for direct comparison with the IMF presented by Sirianni et al. (2000). The 50\% completeness limit for the NICMOS data varies from 2.8 to 1.4 \( M_\odot \) for the four boxes. Following Sirianni et al., we have derived an average completeness limit for the three regions of 2.2 \( M_\odot \). As evident, the agreement is good for the common mass range. We appear to underestimate the stars at \( \sim 6 \ M_\odot \) compared to Sirianni et al. (2000). However those appear to be recovered at 8 \( M_\odot \).

The color–magnitude diagrams show a large spread in the main sequence to pre-main sequence transition at \( F160W = 20 \).
Figure 8. Mass functions for 30 Dor outside 0.6 pc in several annuli after field star subtraction, derived from the luminosity functions. The arrows indicate the 50% completeness limit. Dotted line histograms show the mass functions derived from the uncorrected star counts, whereas the solid line histograms are the completeness corrected mass function. Expected errors due to Poisson noise are indicated on the solid line histograms. A fit is made to the completeness corrected histogram, corrected for field star contamination. The maximum mass used in the fits is $20 M_\odot$. The coefficient shown in each panel is $\Gamma$, $\frac{dN}{d\log M} \propto M^{\Gamma}$. The lower right panel shows the IMF derived by Sirianni et al. (2000) from the areas shown in Figure 2. Further, the plus symbols show the IMF derived from the NICMOS data from the same regions as was used in the Sirianni et al. (2000) study. The 50% completeness is $2 M_\odot$ for this sample, as shown by the arrow.

Table 4

| Age (Myr) | Annulus (pc) | Mass Range ($M_\odot$) | Slope ($\Gamma$) | Mass Range ($M_\odot$) | Slope ($\Gamma$) |
|-----------|--------------|------------------------|------------------|------------------------|------------------|
| 3         | 0.6–1.0      | 8.9–20                 | $-1.7 \pm 0.3$   | ...                    | ...              |
| 3         | 1.0–2.0      | 8.9–20                 | $-1.5 \pm 0.1$   | ...                    | ...              |
| 3         | 2.0–3.0      | 8.9–20                 | $-1.4 \pm 0.2$   | ...                    | ...              |
| 3         | 3.0–5.0      | 1.4–20                 | $-1.2 \pm 0.1$   | ...                    | ...              |
| 3         | 5.0–7.0      | 0.8–20                 | $-0.9 \pm 0.1$   | 1.4–1.7               | $-0.9 \pm 0.2$   |
| 2         | 3.0–5.0      | 1.1–20                 | $-1.0 \pm 0.1$   | 1.1–1.7               | $-1.3 \pm 0.3$   |
| 2         | 5.0–7.0      | 0.7–20                 | $-1.0 \pm 0.1$   | 0.7–1.7               | $-0.8 \pm 0.2$   |
| 4         | 3.0–5.0      | 1.4–20                 | $-1.2 \pm 0.1$   | ...                    | ...              |
| 4         | 5.0–7.0      | 1.1–20                 | $-1.2 \pm 0.1$   | 1.1–1.6               | $-1.3 \pm 0.4$   |
| 2–4       | 3.0–5.0      | 1.4–20                 | $-1.3 \pm 0.1$   | ...                    | ...              |
| 2–4       | 5.0–7.0      | 1.1–20                 | $-1.2 \pm 0.1$   | 1.1–1.6               | $-1.1 \pm 0.4$   |

Note. The slope of a Salpeter IMF in these units is $-1.35$. All the fits were performed over the mass range indicated in the table.
18–19 mag. Although shown in Section 3.2 that this scatter can be explained by differential extinction, it cannot be ruled out that there is an age spread present as well as suggested in previous studies (Hunter et al. 1995; Massey & Hunter 1998). It is therefore reasonable to take a star formation history different than a single burst at 3 Myr into account. We show in Figure 9 the IMF in the outer two annuli assuming a cluster age of 2 and 4 Myr, respectively. We also show an “average” IMF found as the average of the IMF’s derived for the age range 2–4 Myr in 0.5 Myr increments. The lower mass limit in the average IMF was determined from the 4 Myr isochrone which provides the most restrictive mass limit. We find that both in the case of a 2 and 4 Myr isochrone the IMF is well fit by power laws. The derived slopes are steeper assuming an older isochrone relative to the younger ones. There is no indication for a flattening below $2 M_\odot$ in either case. The average IMF is also found to be represented by a power law with a slope consistent with a Salpeter slope. The slopes of the derived power laws are given in Table 4. For the average IMF, the number of stars averaged over the different ages in each mass bin is derived. Error bars for the average IMF have been determined as the standard deviation around the mean number of objects in each mass bin.

As was the case for the 3 Myr isochrone, the slopes of the IMF for different assumed ages have also been calculated and are provided in Table 4. The slopes are found to be shallower than a Salpeter slope, but at the $\sim 2\sigma$ level consistent with a Salpeter slope. The slopes are also consistent with those derived for all masses up to 20 $M_\odot$, as was the case assuming the 3 Myr isochrone.

The lack of a flattening in the IMF below $2 M_\odot$ is in contrast to the results presented by Sirianni et al. (2000), who derived the IMF closer to the cluster center. There can be several possible reasons for the difference in the derived IMF slope in the two

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**Figure 9.** Derived IMFs between 3 and 7 pc assuming a 2 Myr isochrone (top), a 4 Myr isochrone (middle) and an average of the IMFs derived for the 2–4 Myr isochrones in 0.5 Myr increments (bottom). The error bars on the top two panels include Poisson noise and the uncertainties in the completeness corrections. The number of stars in each mass bin in the average IMF is determined as the average of the 5 IMFs for ages 2–4 Myr. The error bars for each bin in the average IMF are then calculated as the standard deviation of the number of stars in the bin. The arrow shows the 50% completeness limit in each panel and the number next to arrow indicates the limiting mass in solar masses. For the average IMF, the 50% completeness limit is determined by the 4 Myr isochrone since here the completeness limit corresponds to the highest mass.
surveys. First, due to the different spatial resolution in the two studies, the NICMOS IMF is derived further away from the center of the cluster than the WFPC2 IMF by Sirianni et al. (2000). The IMF was derived in the areas shown in Figure 2 as regions B, C, and D. Thus, all of their surveyed area is outside a radius of 1 pc and the majority of their surveyed area is between 2 and 5 pc where crowding precludes NICMOS from detecting stars less massive than 2.2 \( M_\odot \) for a 3 Myr isochrone. One possibility for the difference in the derived slopes for the two distributions to be drawn from the same parent distribution is 10%. The implication is that there is no evidence for luminosity segregation in the two annuli.

Another explanation for the difference between the results obtained here and the results by Sirianni et al. (2000) can be mass segregation. We have searched for evidence for mass segregation in the two outer annuli in our survey. We used the LFs instead of the mass functions to avoid additional uncertainties due to the mass–luminosity relation. The results obtained for the mass functions are very similar to those from the LFs.

The cumulative luminosity distributions are shown in Figure 11 for the outer two radial bins. These are the only bins where the 50% completeness limit is below 2 \( M_\odot \). The two cumulative distributions are very similar. We have performed a Kolmogorov–Smirnov test to quantify the similarity of the cumulative luminosity distributions. The maximum difference between the two distributions is 0.039 and the probability for the two distributions to be drawn from the same parent distribution is 10%. Thus, there is no strong evidence (less than 2\( \sigma \)) for mass segregation in the outer parts of the cluster.

The fact that there is little evidence for mass segregation outside 3 pc does not exclude the possibility that the cluster is mass segregated out to a radius of several pc. Both Malumuth & Heap (1994) and Brandl et al. (1996) found evidence for mass segregation of the massive stars in the center of the cluster. Brandl et al. (1996) showed the half-mass relaxation time to be 7.8 \( \times 10^7 \) yr, much longer than the cluster age. They also point out that the massive stars will experience mass segregation on a much shorter timescale than the lower mass stars; the timescale depends inversely on the stellar mass. It is thus not surprising, from a dynamical point of view, that there is no evidence for mass segregation outside the half-mass radius of 1.7 pc (Hunter et al. 1995).

On the other hand, this does not rule out the possibility that the cluster might be mass segregated at birth closer to the

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**Figure 10.** Illustration of the effect on the derived IMF of individual random differential extinction within 30 Dor. The solid line is an artificial Salpeter mass function and the dotted line is the retrieved mass function by adopting a magnitude-limited sample. The magnitude limit was assumed to be the same as used by Sirianni et al. (2000; \( V = 24.7 \) mag). Crosses show the mass function derived by Sirianni et al. (2000). The stair-case shape of the input IMF at the high-mass end is due to finite, yet constant size of the mass bins. The 50% completeness limit at 1.35 \( M_\odot \) is indicated by the arrow.

**Figure 11.** Comparison of two cumulative luminosity distributions outside 3 pc and down to the 50% completeness level of \( F160W = 21 \) mag for the 3–5 pc annulus. A K–S test of the two distributions gives a maximum distance between the two distributions of 0.039 and the probability the two distributions to be drawn from the same parent distribution is 10%. The implication is that there is no evidence for luminosity segregation in the two annuli.

The observed IMF similar to that deduced by Sirianni et al. (2000). The ratio of the number of stars below and above 2 \( M_\odot \) respectively has been calculated both for the model cluster and the data from Sirianni et al. (2000). For the model cluster it is found to be 0.87, which is in reasonable agreement with the ratio of 0.76 derived from the observations.

### 4.3. Cumulative Mass Functions in the Outer Parts of R136

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On the other hand, this does not rule out the possibility that the cluster might be mass segregated at birth closer to the...
cluster center. Evidence for mass segregation has been found in, e.g., the Orion Nebula Cluster (ONC; Hillenbrand & Hartmann 1998; Bonnell & Davies 1998). Hillenbrand & Hartmann (1998) showed evidence for mass segregation down to stellar masses of 1–2 $M_\odot$. Due to the youth of the ONC, they concluded the mass segregation had to be at least partly primordial. It is thus possible that R136 is also affected by primordial mass segregation close to the cluster center and that mass segregation is the reason for the difference between the NICMOS and WFPC2 IMFs.

4.4. Cluster Mass

We can obtain a rough estimate of the cluster mass from the near-infrared observations. The main limitation in our mass estimate is the amount of confusion due to crowding in the cluster center: our data mainly sample the IMF down to and below 1.4 $M_\odot$ outside 3 pc. Nevertheless, we can utilize the mass estimates within 2 pc from Hunter et al. (1995) to complement our mass estimate down to 2.1 $M_\odot$. Inside 2 pc and into 0.15 pc, the results are extrapolated from the local completeness limit mass down to 2.1 $M_\odot$ assuming an underlying Salpeter IMF. No stars have been detected less massive than 20 $M_\odot$ within the central 0.15 pc radius due to crowding. The mass in the very center has been estimated from the surface density profile down to 2.8 $M_\odot$ in Hunter et al. (1995) to be $4 \times 10^5$ $M_\odot$ pc$^{-2}$, resulting in a mass of 3700 $M_\odot$ down to a lower mass limit of 2.1 $M_\odot$. We find the cluster total mass down to 2.1 $M_\odot$ to be $5 \times 10^4$ $M_\odot$. The directly determined mass down to 2.8 $M_\odot$ within 4.7 pc is found to be $2.0 \times 10^4$ $M_\odot$, almost the same as found by Hunter et al. (1995). If the IMF follows a Salpeter slope down to 0.5 $M_\odot$ as observed in the Galactic field and nearby lower mass clusters (Kroupa 2002), the total mass in the central region would be roughly double the amount given above, and the total cluster mass would be close to $\sim 10^5$ $M_\odot$.

The velocity dispersion, and hence the dynamical mass, of the whole NGC 2070 region, including R 136 has been determined by Bosch et al. (2009). The dynamical mass was determined to be $4.5 \times 10^5$ $M_\odot$, almost 5 times higher than expected for R 136 alone, but consistent with the photometric mass for the same area (Selman et al. 1999). If we take into account that the half mass radius of R 136 is 1.7 pc (Hunter et al. 1995), compared to 14 pc for the whole NGC 2070 region and assuming the velocity dispersion is the same in the inner parts of the cluster, we would expect a dynamical mass of $4.5 \times 10^5 \times 1.7/14$ $M_\odot = 5.5 \times 10^4$ $M_\odot$ which is lower than the mass expected if the IMF is consistent with a Galactic IMF down to 0.5 $M_\odot$. Thus, at face value, the velocity dispersion would be low enough that the cluster can stay bound. However, a measurement of the velocity dispersion for the inner regions is necessary to directly compare the photometric mass with the dynamical mass.

4.5. The Surface Brightness Profile

We can directly derive the surface brightness profile of the region around R136 in the 30 Dor cluster since the data do not suffer from saturated stars. Although bright stars will saturate through the 1 hr exposure, the non-destructive readout mode ensures that only the first reads are used to derive the magnitude of the brightest stars. The surface brightness profile is shown in Figure 12.

Between $\sim 0.2$ and 2 pc, the light profile is well fit by a power law, whereas inside 0.2 pc the light profile appears to be flattening. We have therefore fitted the light profile with a power law modified by a core radius, similar to the approach in

Figure 12. Surface brightness profile of the R136 cluster within a 7 pc radius of the cluster center. The solid line is a pure power-law fit from 0.02 pc to 2 pc with a derived slope of $-1.48$. The dashed line is an Elson, Fall, & Freeman-type profile with a core radius of 0.025 pc and a power-law slope of $-1.54$ (Elson et al. 1987). The fit was done from 0.009–2 pc. Beyond 2 pc, the presence of the individual bright stars labeled in Figure 2 introduces the jitter seen in the surface brightness profile.

Elson et al. (1987). Constraining the fit to inside 2 pc, we find a slope of $-1.54 \pm 0.02$, slightly more shallow than $-1.72 \pm 0.06$ derived outside 0.1 pc by Campbell et al. (1992) using F336W Planetary Camera onboard HST observations.

The core radius is found to be 0.025 $\pm 0.004$ pc, which is less than the resolution of the observations and is thus likely and upper limit. Previous HST optical studies determined a small core radius, $r_c \leq 0.02$ pc (Hunter et al. 1995), consistent with our findings here. However, since the derived core radius is smaller than the resolution of the observations, its evidence is weak. One or two bright stars off center by only a small amount could mimic a cluster core.

4.6. Comparison with other Massive Clusters and the Implications of Low-mass Stars in R136

How does the low-mass end of the IMF in 30 Dor compare with that determined for other massive and dense stellar clusters? A top-heavy IMF in massive dense clusters has been suggested on theoretical grounds (e.g., Silk 1995). The most convincing example of a young cluster with a present-day mass function departing significantly from a Salpeter IMF above $1 M_\odot$ is the Arches cluster (Stolte et al. 2002; Figer et al. 1999). The most convincing example of a young cluster with a present-day mass function departing significantly from a Salpeter IMF above $1 M_\odot$ is the Arches cluster (Stolte et al. 2002; Figer et al. 1999). Stolte et al. (2002) found an average slope of $\Gamma = -0.9 \pm 0.15$ for the central parsec of the Arches cluster, flatter than a Salpeter slope of $-1.35$. Deeper observations found that the present day mass function in Arches to be well approximated by a power law with a slope of $\Gamma = -0.91 \pm 0.08$ down to 1.3 $M_\odot$ (Kim et al. 2006). However, recent work taking differential extinction into account suggests the slope of the power law is only slightly more shallow than a Salpeter slope, $\Gamma = -1.1 \pm 0.2$ (Espinoza et al. 2009). Portegies Zwart et al. (2002) noted that even if the observed IMF is slightly flatter than Salpeter IMF, this can be explained by mass segregation. The mass segregation would be accelerated in the cluster due to the strong gravitational field from the Galactic Center. By adopting realistic parameters for a model cluster and an appropriate distance from the Galactic center, they found that an input Salpeter slope IMF would be
transformed to the observed present day mass function via strong dynamical evolution. Stolte et al. (2006) showed that the IMF of the cluster powering the NGC 3603 H II region was well fitted by a power law but with a slope flatter than Salpeter, $\Gamma = -0.91 \pm 0.15$. They further showed evidence for mass segregation for the more massive stars, $M > 4 M_\odot$. The data indicated a slight flattening of the low-mass content ($M < 3 M_\odot$). NGC 3603 is younger than the Arches cluster and not affected by a strong tidal gravitational field. Thus, it is expected to be less influenced by dynamical mass segregation.

The even more massive starburst clusters appear to be the primary sites (unit cells) of star formation in starburst galaxies, including interacting/colliding galaxies such as The Antennae or The Cartwheel. If starburst clusters are the basic building blocks of certain star-forming galaxies, their stellar content (IMF) will affect much of the observed chemical and photometric evolution of galaxies, both at the present epoch and perhaps even more so in the high-redshift past (Charlot et al. 1993). Several observational claims have been made that the IMF in unresolved starburst clusters is top heavy (Rieke et al. 1993), although observations of the Antennae gave a mixed result (Mengel et al. 2002). However, it has been suggested that the high mass-to-light ratios found in some young starburst clusters are artificially high related to their not being in virial equilibrium due to gas expulsion from the clusters (Goodwin & Bastian 2006). During the first 50 Myr of the cluster, the velocity dispersion and hence the cluster mass might be overestimated if the cluster is assumed to be virialized. Goodwin & Bastian (2006) suggested that the top-heavy IMFs inferred in young unresolved extragalactic star clusters might be spurious due to their non-virialized dynamical state.

With the present data set it is clear that the IMF in the outer parts of R136 continues as a power law down to $1 M_\odot$, similar to what is found in other star clusters and the slope is similar to what is found in the field. Whether this is true for the cluster as a whole depends on the cause for the flattening observed closer to the cluster center. It would be interesting to know the IMF if the observations could be extended closer to the characteristic mass where the Galactic field star IMF flattens ($0.5 M_\odot$; Kroupa 2002), a mass that can be reached in massive young clusters ($\leq 4$ Myr) in the LMC with AO systems.

It has long been suggested R136 might be a proto-globular cluster (Meylan 1993; Larson 1993). The question has been whether R136 would remain bound over a Hubble time. One consequence of a top-heavy IMF is that the cluster would dissolve soon after gas expulsion and mass loss due to evolution of the high-mass stars. However, the detection of stars in R136 less massive than $1 M_\odot$ gives the first direct evidence that low-mass stars are formed in a starburst cluster. The fact that the IMF in the outer parts of R136 appears to be a Salpeter IMF down to at least $1 M_\odot$ gives support to the notion the cluster might be a proto-globular cluster, albeit a light one. Early gas expulsion and subsequent mass loss through stellar evolution will disrupt star clusters deficient in low-mass stars during the first 5 Gyr of the clusters life (Chernoff & Weinberg 1990; Goodwin 1997). However, a determination of the velocity dispersion in the inner parts of the cluster is necessary to determine its final fate. Thus, the presence of low-mass stars is a necessary, but not sufficient condition for the possibility of the cluster to evolve into a globular cluster. The median mass of Galactic globular clusters is $8.1 \times 10^4 M_\odot$ (Mandushev et al. 1991), comparable to the mass of R136. Even if R 136 will remain bound it will lose some mass and might end up as a low-mass globular cluster.

5. CONCLUSIONS

We have analyzed HST/NICMOS F160W band data covering the central 14 pc $\times$ 14.25 pc around R136 in the NGC 2070 cluster in the LMC. We have reached the following conclusions.

1. From the color–magnitude diagram obtained by combining our photometry with previously published HST/WFPC 2 F555W data we constrain the age of the lower mass stellar content in the cluster to be 2–4 Myr, consistent with previous estimates. We derive individual masses for the objects detected adopting a 3 Myr isochrone.

2. We have detected stars in the cluster down to $0.5 M_\odot$ at $r > 5$ pc, assuming an age of 3 Myr.

3. The derived IMF is consistent with a Salpeter slope IMF with no evidence for a flattening at low masses down to the 50% completeness limit corresponding to a mass of $1.1 M_\odot$ outside a radius of 5 pc for a 3 Myr population and $1.4 M_\odot$ if the oldest stars are 4 Myr.

4. The result is in disagreement with the flattening of the IMF below $2 M_\odot$ observed by Sirianni et al. (2000) using optical data covering a region closer to the cluster center. We suggest two possible reasons for the discrepancy: differential extinction and mass segregation.

5. We find no evidence for mass segregation outside 3 pc, but with the current data, we cannot rule out that closer to the center the low-mass stars are segregated.

6. From the radial surface brightness profile we have derived a core radius for the cluster of 0.025 pc ($0^\prime\prime.1$), consistent with previous estimates by Hunter et al. (1995).

7. The mass of the cluster within 7 pc between 25 $M_\odot$ and down to 2.1 $M_\odot$ is estimated to be $5 \times 10^5 M_\odot$. If the IMF continues with a Salpeter slope down to $0.5 M_\odot$ the total mass estimate will double.

8. The total mass of the cluster combined with the large number of low-mass stars suggests that the 30 Dor cluster may survive to become a proto-globular cluster depending on the cluster velocity dispersion.

We thank Richard Larson for discussions in the early phases of the project, Eddie Bergeron for assistance with the drizzle software, and Matthew Kenworthy for commenting on an early version of the manuscript. M.A. and H.Z. acknowledge support from the DLR grant 50OR9912: “Data analysis of NICMOS/HST images of the 30 Dor cluster” and partial funding through the DLR grant 50OR0401. M.A. thanks the Astrophysikalisches Institut Potsdam for providing a stimulating and supportive environment for carrying out this Thesis work. Additional support was funded through the European Commission Fifth Framework Programme Research Training Network “The Formation and Evolution of Young Stellar Clusters” (HPRN-CT-2000-00155). The Astronomische Gesellschaft is acknowledged for providing funding for travel. Support for this work was provided by NASA through grant no. GO-07370.01-96A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

Facilities: This paper is based on observations made with the NASA/ESA HST, operated by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.
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