NEW CONSTRAINTS ON MASS-DEPENDENT DISRUPTION OF STAR CLUSTERS IN M51

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ABSTRACT

We use UBV I Hα images of the Whirlpool galaxy, M51, taken with the Advanced Camera for Surveys and WFPC2 cameras on the Hubble Space Telescope (HST) to select star clusters, and to estimate their masses and ages by comparing their observed colors with predictions from population synthesis models. We construct the mass function of intermediate-age (1–4 × 10⁸ yr) clusters, and find that it is well described by a power law, \( \psi(M) \propto M^{\beta} \), with \( \beta = -2.1 \pm 0.2 \), for clusters more massive than \( M \approx 6 \times 10^3 \, M_\odot \). This extends the mass function of intermediate-age clusters in M51 to masses lower by nearly a factor of five over previous determinations. The mass function does not show evidence for curvature at either the high or low mass end. This shape indicates that there is no evidence for the earlier disruption of lower mass clusters compared with their higher mass counterparts (i.e., no mass-dependent disruption) over the observed range of masses and ages, or for a physical upper mass limit \( M_c \) with which clusters in M51 can form. These conclusions differ from previous suggestions based on poorer-quality HST observations. We discuss their implications for the formation and disruption of the clusters. Ages of clusters in two “feathers,” stellar features extending from the outer portion of a spiral arm, show that the feather with a larger pitch angle formed earlier, and over a longer period, than the other.

Key words: galaxies: individual (M51) – galaxies: starburst – galaxies: star clusters: general – stars: formation

1. INTRODUCTION

The disruption of star clusters plays an important role in building up the stellar populations of galaxies. While most stars form in groups and clusters, the majority of these clusters disrupt quickly, releasing their remaining stars to the field. However, the details of how clusters disrupt, e.g., the physical processes that dominate disruption on different timescales are still controversial. We have previously suggested that the early disruption of clusters for the first \( \tau \lesssim \) few × 10⁸ yr does not depend strongly on the mass of the clusters or on the type of host galaxy. In this “quasi-universal” picture, the distribution of cluster masses and ages \( g(M, \tau) \) is quite similar from galaxy to galaxy, although it may be modulated somewhat by different densities of molecular material within galaxies for ages \( \tau \gtrsim 10^6 \) yr (see, e.g., Fall et al. 2005, 2009; Whitmore et al. 2007; Chandar et al. 2010a for details). Variations in the rate of cluster formation will also affect \( g(M, \tau) \), even if the disruption rate is identical in different galaxies, although the observational evidence so far suggests that these variations are modest (see discussion in Chandar et al. 2010b). A different picture, where the time it takes a cluster to disrupt depends both on its mass and on its host galaxy, has been suggested by Lamers et al. (2005); we will refer to this as the “galaxy-dependent” picture.

Observations of the cluster system in M51 have played a central role in the development of the galaxy-dependent picture of cluster disruption. Assuming that clusters disrupt as a power law with mass, such that the disruption timescale \( \tau_d = \tau_c \left( M/10^3 \right)^k \), where \( \tau_c \) is the characteristic time it takes a 10³ \( M_\odot \) cluster to disrupt, Boutloukos & Lamers (2003), Lamers et al. (2005), and Gieles et al. (2005) suggested that clusters in M51 disrupt with parameters \( k \approx 0.6 \) and \( \tau_c \approx 1–2 \times 10^8 \) yr, i.e., that clusters in M51 disrupt on fairly short timescales. These results were based on masses and ages of clusters determined from two pointings with WFPC2 on the Hubble Space Telescope (HST; see, e.g., Figure 1 in Bastian et al. 2005).

By contrast, it was suggested that clusters in the Magellanic Clouds have significantly longer disruption times than in M51, with \( \tau_c \approx 8 \times 10^9 \) yr (Boutloukos & Lamers 2003; Lamers et al. 2005; de Grijs & Anders 2006). In the galaxy-dependent picture, these strong variations in \( \tau_c \) are explained by differences in the strength of the tidal field (Lamers et al. 2005) and in the density of giant molecular clouds (Gieles et al. 2006a) from galaxy to galaxy.

Recently, we did not find evidence for mass-dependent disruption of clusters in the Magellanic Clouds, and we found that the value of \( \tau_c \approx 8 \times 10^9 \) yr suggested previously implies observed masses and ages which are below those available in current cluster catalogs (e.g., see Figures 3 and 5 in Chandar et al. 2010a). Similarly, we did not find observational evidence for the mass-dependent disruption of clusters (with ages \( \tau \lesssim 4 \times 10^8 \) yr) in the nearby spiral galaxy M83 (Chandar et al. 2010b), despite the fact that it has a similar morphology, metallicity, and molecular mass as M51.7

Given the suggestion of a short disruption time for clusters in M51, and the critical role this plays in the galaxy-dependent

7 M83 and M51 have a similar metallicity (see Bresolin & Kennicutt 2002 for M83 and Moustakas et al. 2010 for M51). The total mass of molecular gas in M51 (2 × 10⁶ \( M_\odot \); Schuster et al. 2007) is within a factor of two of the mass of molecular gas in M83 (3.9 × 10⁶ \( M_\odot \); Lundgren et al. 2003).
disruption picture, it is important to check the previous results. Here, we determine masses and ages of star clusters in M51 using the best available HST observations, which are deeper, have better spatial coverage, and higher angular resolution than used in the works mentioned above, in order to assess the validity of the previous claims. We focus on constructing the mass function of intermediate-age ($1 \times 10^8$ yr) clusters, because a characteristic disruption timescale $\tau_* \approx 2 \times 10^8$ yr should be observable as significant flattening or curvature in the mass function of clusters at this age, above the completeness limit of the data. We also use the mass function to assess previous suggestions for a physical upper mass limit of $M_C \approx 1 \times 10^5 M_\odot$ with which clusters in M51 can form (e.g., Gieles et al. 2006b; Gieles 2009). A third goal is to investigate the ages of clusters located in two “feathers,” stellar features found between the spiral arms, which are expected, based on simulations, to have ages of $\approx 10^8$ yr.

This paper is organized as follows. Section 2 presents the data, cluster selection, and photometry used in this work. Section 3 describes our technique for determining the masses and ages of the clusters, and Section 4 presents the mass function for intermediate-age ($1 \times 10^8$ yr) clusters in M51 for two samples, a shallower sample covering the entire galaxy and a deeper one covering a $\approx 3 \times 7$ kpc$^2$ area with low background and little crowding, located on the west side of the galaxy (hereafter referred to as Region 1). Section 5 discusses implications of the shape of the mass function in terms of the formation and disruption of the clusters, and also presents some new results for the ages of clusters in two “feathers” located within Region 1. Section 6 summarizes the main results of this work.

2. OBSERVATIONS AND CLUSTER SELECTION

Observations of M51 (i.e., NGC 5194, a Sbc galaxy) and its companion NGC 5195 (a SB0 galaxy) were made in 2005 January with the HST using the Wide Field Channel of the Advanced Camera for Surveys (ACS/WFC), as part of HST’s 15th year on-orbit celebration (Program GO-10452; PI: S. Beckwith). Imaging was obtained in the following optical filters: F435W (“B”), F555W (“V”), F814W (“I”), and the F658N filter which targets Hα+[N II] emission at the recessional velocity of M51 (referred to here as the “Hα” filter). Details of the data and image processing are given at a dedicated Web site, and result in a mosaic image in each filter with a pixel scale of 0’05 pixel$^{-1}$, or 2 pc pixel$^{-1}$ at the assumed distance of 8.4 Mpc for M51 (distance modulus $m - M = 29.62$; Feldmeier et al. 1997). A portion of the resulting image is shown in Figure 1.

We have also obtained images for six pointings in M51 with the F336W filter (“U”) of the WFPC2 camera as part of program GO-10501 (PI: R. Chandar), which was designed to work in concert with the Hubble Heritage program. There are two additional pointings available with the F336W filter, which cover the nuclear region of M51 (GO-5652, PI: R. Kirshner and GO-7375, PI: N. Scoville). The raw data were processed through the standard WFPC2 pipeline (CALWP2) using the most recent flatfield, bias and dark current reference frames. The resulting calibrated images were co-added to create a single mosaic image using the MULTIDRIZZLE task to reject cosmic rays, identify bad pixels, and correct the geometric distortion. The final mosaic was created using data primarily taken with the Wide Field (WF) CCDs, with Planetary Camera (PC) data, which have a different scale, used only to cover regions where WF data are absent. Our U-band mosaic is shown in Figure 2. The resolution of the U-band mosaic is 0’1 pixel$^{-1}$ corresponding to 4 pc pixel$^{-1}$, and covers $\approx 60\%$ of the luminous portion of the ACS mosaic, including some portions of Region 1.

8 http://archive.stsci.edu/prepds/m51/ 9 We excluded the WF4 chip of the dataset U9GA0601B from the mosaic, because it is badly affected by the WF4 CCD bias anomaly.
We detect sources, both point-like and slightly extended, on a summed \( BVI \) image, and perform circular aperture photometry on the drizzled mosaic image in each filter using the IRAF task PHOT, using an aperture radius of 2.5 pixels and a background annulus between 10 and 13 pixels. For the narrowband \( H\alpha \) image, we perform photometry on the image without subtracting the stellar continuum flux. We convert the instrumental magnitudes to the VEGAMAG magnitude system by applying the zero points given in Sirianni et al. (2005) for the ACS filters, and given in Holtzman et al. (1995) for the WFPC2. The F336W photometry was also corrected for the effects of charge transfer inefficiency, using the prescription given by Dolphin (2000).\(^{10}\) The full catalog contains \( \approx 236,000 \) sources, and includes individual stars, close blends of a few stars, star clusters, and a few background galaxies. We use two different approaches to determine aperture corrections for our sources: (1) we apply a typical value to all clusters; and (2) we determine an individual aperture correction based on the size measured for the objects, specifically their concentration index \( (C, \text{ defined as the difference in the aperture magnitudes determined using a 3 pixel and a 0.5 pixel radius}) \), similar to the procedure used in Chandar et al. (2010b).

In addition to the concentration index, we measure the size of each source in our catalog using the Ishape software (Larsen 1999). While the \( C \) index is a very simple method that works well for most clusters, it provides a much cruder measure of object size than Ishape. Ishape convolves analytic profiles of different effective radii, \( R_{\text{eff}} \), representing the surface brightness profile of a cluster, with the point-spread function (PSF), and determines the best fit to each source. It returns a measure of the FWHM of a source in pixels, i.e., how much broader a source is than the PSF. In general, Ishape can distinguish sources that are broader than the PSF by \( \approx 0.2 \) pixels or more (e.g., Larsen 1999). We created a PSF for the \( V \)-band image from \( \approx 30 \) relatively bright, isolated point sources, and assume a King profile (King 1966) with a ratio of tidal to core radius of 30. Ishape returns the best-fit radius of each source, where the fit is performed within a 5 pixel radius.

We construct two different catalogs of star clusters. First, we select clusters over the entire image, but restrict our sample to objects brighter than \( V \approx 23 \) mag, because the contamination due to blends increases significantly below this luminosity in the most crowded spiral arm and high background inner regions of M51. Second, we focus on a large, \( \approx 3 \times 7 \) kpc\(^2 \) area of M51 with low background, which also contains many intermediate-age (1–4 \times 10^8 yr) clusters (see Section 3). In this area, shown by the rectangle in Figure 1, we are able to select star clusters down to \( V \approx 24.7 \) mag, and hence to construct the mass function down to significantly lower masses.

In order to select star clusters in M51 from our full source catalog, which contains mostly individual stars and clusters, we follow the general approach described in Whitmore et al. (2010) and Chandar et al. (2010b), where we construct “training sets” of stars and clusters and use their measured properties to guide the criteria used to automatically select clusters. In addition to selecting good clusters, we need to minimize contamination in our candidate cluster catalog from close pairs of individual stars. We use the following criteria to select cluster candidates in M51: (1) \( 1.1 \leq C \leq 2.0 \), (2) \( 0.2 \leq \text{FWHM} \leq 2.0 \) pixel, (3) eliminate sources which satisfy (1) and (2) but have another detection within 2 pixels, and (4) select the brightest object within a 5 pixel radius which satisfies (1) and (2). These criteria are similar to those used to select clusters in WFC3 observations of M83 (Chandar et al. 2010b). Visual inspection of candidate clusters confirms that we select nearly all obvious clusters down to our magnitude limit while including relatively few contaminants (mostly blends of a few stars, at the \( \approx 10\%–15\% \) level) in our candidate cluster list. The full catalog contains a total of \( \approx 3500 \) cluster candidates brighter than \( m_V \approx 23 \), and Region 1 contains \( \approx 2400 \) clusters brighter than \( m_V \approx 24.7 \). The catalogs contain clusters from a few \( \times 10^5 \) yr to \( \approx 10^{10} \) yr, based on age estimates made in Section 3. We note that our cluster catalog in Region 1 is deliberately biased against the youngest clusters, which are preferentially located in and near the inner spiral arms, but instead contains a rich population of intermediate-age clusters, making it ideal for the purposes of this study. The youngest clusters (\( \tau \lesssim 10^7 \) yr) from our M51 catalog are used in Calzetti et al. (2010) to investigate the upper end of the stellar initial mass function (IMF), and the entire sample will be used to determine the cluster age distribution in a forthcoming study (R. Chandar et al. 2011, in preparation).

Incompleteness in our cluster catalog disproportionately affects faint clusters, which are easier to miss in the data. We assess the completeness of our sample by adding artificial clusters throughout the image, and then subjecting them to our selection criteria. These experiments indicate that our sample is fairly complete (at \( \approx 90\% \) level) for a typical cluster size down to \( m_V \approx 24.7 \) in Region 1, but that a similar level of completeness occurs closer to \( m_V \approx 23 \) in the crowded spiral arms. Our \( 90\% \) completeness limit corresponds roughly to a mass of \( 6 \times 10^3 \) \( M_\odot \) for a cluster at an age of \( \tau \approx 2 \times 10^8 \) yr. Figure 3 shows that clusters with masses \( \approx 6–8 \times 10^3 \) \( M_\odot \) and ages \( \approx 1–3 \times 10^8 \) yr are quite easy to detect in Region 1.

### 3. MASS AND AGE DETERMINATIONS

We estimate the age \( (\tau) \) and extinction \( A_V \) of each cluster as we have done in previous works (see Fall et al. 2005; Whitmore et al. 2010 for details), by performing a least \( \chi^2 \) fit comparing the measurements in five filters \( (UBVI, H\alpha) \) with predictions from the Bruzual & Charlot stellar population models (G. Bruzual 2007, private communication; Bruzual & Charlot 2003). We have assumed solar metallicity \( Z = 0.02 \) (appropriate for young clusters in M51; Moustakas et al. 2010), a Salpeter (1955) stellar IMF, and a Galactic-type extinction law (Fitzpatrick 1999).

The best-fit values of \( \tau \) and \( A_V \) are those that minimize

\[
\chi^2(\tau, A_V) = \sum_\lambda W_\lambda (m_\lambda^{\text{obs}} - m_\lambda^{\text{mod}})^2,
\]

for each cluster, where \( m_\lambda^{\text{obs}} \) and \( m_\lambda^{\text{mod}} \) are the observed and model magnitudes respectively, and the sum runs over all five bands, \( \lambda = U, B, V, I, \) and \( H\alpha \). In regions where no \( U \)-band imaging is available, ages are determined from the \( BVI, H\alpha \) filters. The weight factors in the formula for \( \chi^2 \) are taken to be \( W_\lambda = \sigma_\lambda^2 + (0.05 \sigma_\lambda)^2 \), where \( \sigma_\lambda \) is the formal photometric uncertainty determined by PHOT for each band. The mass of each cluster is estimated from the observed \( V \)-band luminosity, corrected for extinction, and the (present-day) age-dependent mass-to-light ratios \( (M/L)_\lambda \) predicted by the models.

Our inclusion of photometry in the narrowband \( H\alpha \) filter directly in our fitting procedure (currently unique among studies of extragalactic star cluster systems) helps to break the degeneracy between age and extinction that exists in the broadband colors.

\(^{10}\) See http://purcell.as.arizona.edu/wfpc2_calib/ for the more recent formulae.
Figure 3. Figure showing a portion of Region 1. Some intermediate-age (τ ≈ 1–4 × 10^8 yr) clusters with estimated masses of ≈ 4–8 × 10^3 M⊙ are circled. Clusters with these properties are easy to detect and clearly broader than the PSF in the ACS images.

of young star clusters. Most important for this work, the narrowband filter provides a fourth photometric measurement for clusters where there is no U-band imaging available, including portions of Region 1. The narrowband filter not only provides photometric measurements for clusters that have H II regions and hence strong Hα emission, but also for older clusters, since it contains both (nebular) line and (stellar) continuum emission. In clusters older than ≈10^7 yr this filter gives a measure of the continuum in the ≈R band.

In R. Chandar et al. (2011, in preparation), we provide a detailed assessment of the uncertainties in our age estimates, compare our photometric ages with those derived using other techniques for various cluster subsamples, and provide basic information on the most massive clusters in M51. Here, we compile a list of clusters with estimated ages between 1 and 4 × 10^8 yr, the age range relevant for this work, based on measurements in all five UBVRI,Hα filters. We compare these ages with ages derived from different filter combinations. We find that the ages of ≈85%–90% of these clusters are recovered to within 0.3 dex when determined from measurements in BVI,Hα, ≈70%–75% are recovered from measurements in UBVRI, and only ≈50% are recovered when BVI measurements are used with our dating method (in the last case approximately half the clusters are assigned a younger age and relatively high extinction).

Next, we discuss uncertainties in our mass determinations. We have assumed a Salpeter IMF; if we had adopted the more modern Chabrier (2003) IMF instead, the M/LV and hence the masses would decrease by a near constant (age-independent) ≈40%.11 The difference between assuming mean and size-dependent aperture corrections can result in relatively large variations in the total magnitude for a given cluster (for our age determinations we use aperture magnitudes, which lead to small uncertainties in cluster colors). However, in Section 5 we find that the specific method used to determine aperture corrections has a negligible effect on the mass function itself.

4. MASS FUNCTION

The shape of the mass function for intermediate-age star clusters provides one of the most important constraints on the disruption of the clusters. Figure 4 shows the mass function, dN/dM, for intermediate-age (8.0 ≤ log(τ/yr) ≤ 8.6) clusters in Region 1 (top panel), and in the full sample (bottom panel).
The mass function reaches lower masses in Region 1 than in the full sample because of the lower background and crowding, as discussed in Section 2. We have used masses determined from cluster luminosities based on our preferred, size-dependent aperture corrections, although the results are quite similar if we use total magnitudes based on an average aperture correction instead (see below). Two different binnings are shown: variable size bins with equal numbers of clusters in each bin (as recommended by Maiz Apellaniz & Ubeda 2005) and as filled circles, and approximately equal size bins with variable numbers of clusters in each bin (open circles).

These mass functions can be described by a power law, \( dN/dM \propto M^\beta \). We perform simple least-squares fits to the mass functions, which give formal fits of \( \beta = -2.02 \pm 0.09 \) when using variable size bins, nearly identical to the value of \( \beta = -2.00 \pm 0.06 \) found from equal size bins for \( M > 6 \times 10^3 M_\odot \) for intermediate-age clusters in Region 1. If we use masses determined when an average aperture correction is applied to the cluster photometry instead of size-dependent aperture corrections, we find nearly identical results, with \( \beta = -2.05 \pm 0.09 \) (variable size bins) and \( \beta = -2.03 \pm 0.06 \) (equal size bins). For the full sample and variable size bins, the fits are \( \beta = -2.25 \pm 0.09 \) and \( \beta = -2.24 \pm 0.20 \) when using size-dependent and average aperture corrected luminosities and masses, respectively. Hence \( \beta \) is nearly the same for the two different samples, within the uncertainties. We find an overall value of \( \beta = -2.1 \pm 0.2 \) for the mass function of 1–4 \( \times 10^8 \) yr clusters in M51, the mean and approximate range of the fits determined for Region 1 and for the entire portion of M51 covered by the ACS observations.

Our results for the mass function of star clusters in M51 are in good agreement with the earlier one from Bik et al. (2003), who found a power-law index of \( \beta = -2.1 \pm 0.3 \) for clusters in M51 based on shallower WFPC2 observations, and within the uncertainties of the values of \( \beta = -1.68 \pm 0.33 \) (for clusters with \( 8.0 \leq \log (\tau/yr) < 8.3 \)) and \( \beta = -1.81 \pm 0.27 \) (for clusters with \( 8.3 \leq \log (\tau/yr) < 8.5 \)) found by Hwang & Lee (2010). It is different, however, from the steep value of \( \beta = -2.76 \pm 0.28 \) (for clusters more massive than \( 6 \times 10^3 M_\odot \) and with ages of \( \tau = 1–6 \times 10^8 \) yr) found by Gieles (2009), but similar to \( \beta = -2.09 \pm 0.09 \) for \( 10^7–10^8 \) yr clusters with \( M > 10^4 M_\odot \) found by Gieles (2009).

5. DISCUSSION

Here we use the observed shape of the mass function of 1–4 \( \times 10^8 \) yr clusters in M51 to investigate two issues related to the formation and disruption of the clusters. First, we assess whether or not our observations support previous suggestions for a physical upper mass limit with which clusters in M51 can form. Next, we assess the validity of the specific mass-dependent disruption model that has been claimed for clusters in M51, and discuss the implications of our results for the galaxy-dependent disruption picture for star clusters. Finally, we investigate the ages of clusters in two “feathers” located within Region 1.

5.1. Constraints on an Upper Mass Cutoff

The upper end of the mass functions of old globular star clusters are typically better fit by a Schechter function, \( \psi(M) \propto M^\beta \text{exp}(-M/M_c) \), with a cutoff of \( M_c \approx 1–2 \times 10^6 M_\odot \), than by a power law (e.g., Burkert & Smith 2000; Fall & Zhang 2001; Jordan et al. 2007). Some recent works have suggested that a Schechter function may also better describe the mass function of young \( \tau < \) few \( \times 10^8 \) yr clusters in nearby spiral galaxies, but with a lower cutoff of \( M_c \approx 2 \times 10^5 M_\odot \) (e.g., see Portegies Zwart et al. 2010, and references therein).

Figure 4 compared the observed mass function of clusters in M51 with a power law, and the upper panel of Figure 5 compares the observed mass function with Schechter functions for three different values of \( M_c: 2 \times 10^5 M_\odot, 4 \times 10^5 M_\odot, \) and \( 10^6 M_\odot \). These figures suggest that a single power law provides a better fit to the observations than a Schechter function with \( M_c \approx 2 \times 10^5 M_\odot \), because there are too many massive star clusters present compared with predictions from the latter. More quantitatively, when we compare a power law with the best-fit index from Figure 4 of \( \beta = -2.03 \) (\( \beta = -2.25 \)) with the mass function for clusters with \( M > 10^5 M_\odot \), a K-S test returns a \( P \)-value of 0.74 (0.92) for Region 1 (all of M51). Hence a power law provides an acceptable fit (has a \( P \)-value >0.05) to the upper end of the mass function, with no significant deviation either visually or statistically. Our data, therefore, do not prefer a Schechter function over a power law.

If we do fit a Schechter function to the observed mass function, we find a best fit of \( \beta = -2.01 \) and \( M_c \approx 10^{12} M_\odot \), i.e., essentially a power law. If we assume a Schechter function with \( \beta = -2.0 \), we can rule out \( M_c \) values of \( 2 \times 10^5 M_\odot \) with high statistical confidence, since a K-S test returns a \( P \)-value of only \( 4 \times 10^{-4} \), with lower values of \( M_c \) giving even lower \( P \)-values. Any value of \( M_c > 2 \times 10^5 M_\odot \) therefore gives a statistically acceptable fit to the observations, within a 95% confidence interval. This is consistent with the \( M_c \approx 1–2 \times 10^6 M_\odot \) found for old globular clusters.

Figure 5. Mass function for 1–4 \( \times 10^6 \) yr clusters in Region 1 is compared with predictions for an upper mass cutoff \( M_c \) (upper panel) and for different characteristic disruption timescales \( \tau_a \) (lower panel). Solid circles show the results for variable bin widths and the open circles show fixed bin widths. The curves in the upper panel are Schechter functions, with \( \psi(M) \propto M^\beta \text{exp}(-M/M_c) \), for \( M_c = 2 \times 10^5 M_\odot, 4 \times 10^5 M_\odot, \) and \( 1 \times 10^6 M_\odot \) (dashed curves). The curves in the lower panel use Equations (B6)–(B8) from Fall et al. (2009) to predict the evolution of the mass function for a population of \( \tau \approx 8.0–8.6 \) yr clusters, with the indicated disruption timescales \( \tau_a \), for an assumed exponent \( k = 0.6 \). See the text for details.
This is a different conclusion than that reached by Gieles et al. (2006b) and Gieles (2009), who suggested that the mass function for clusters in M51 is better fit by a Schechter function with \( M_C \approx 2 \times 10^4 M_\odot \) than by a power law.\(^{12}\) However, the Gieles et al. results were based on WFPC2 observations that have limited coverage of M51. We find that these WFPC2 observations miss nearly 2/3 of the 50 most massive clusters with ages between 1–4 \( \times 10^8 \) yr found in our full sample, including the few most massive objects. This may indicate that small number statistics, and hence the absence of a few massive clusters, can significantly affect tests for a Schechter-like cutoff. We found a similar result for clusters in M83, another grand-design spiral galaxy (Chandar et al. 2010b), where a power law provides a good fit to the observed mass function, without requiring an exponential cutoff (Chandar et al. 2010b). Taken together, our results do not support previous suggestions for a universal cutoff \( M_C \approx 1–2 \times 10^5 M_\odot \) for spiral galaxies.

5.2. Constraints on Mass-dependent Disruption

Some processes, such as the evaporation of stars due to internal relaxation, are known to disrupt lower mass clusters earlier than higher mass clusters. Mass-dependent disruption processes can be detected directly, because they lead to curvature or flattening in the mass function of clusters at lower masses.

The mass function presented for Region 1 in Figure 4 is the deepest to date for intermediate-age clusters in M51, and hence well suited for establishing the presence or absence of bends. In the bottom panel of Figure 5 we compare the observed mass function for intermediate-age clusters in M51 with predictions from the gradual, mass-dependent cluster disruption model suggested by Boutloukos & Lamers (2003), with formulae derived by Fall et al. (2009). The model assumes that the mass \( M \) of a cluster evolves with time \( \tau \) according to the equations

\[
\frac{dM}{d\tau} = -M/\tau_d(M),
\]

\[
\tau_d(M) = \tau_* (M/M_*)^k,
\]

where the exponent \( k \) and characteristic disruption timescale \( \tau_* \) are adjustable parameters, while \( M_* = 10^8 M_\odot \) is a fiducial mass scale. We assume that the initial cluster mass function is a power-law with \( \beta = -2.0 \).\(^{13}\) Equations (B6)–(B8) in Fall et al. (2009) give the analytic expressions derived for the mass function of star clusters in different intervals of age in the case of gradual, mass-dependent disruption, and can be compared directly with observations. The lowest curve, which shows \( \tau_* = 2 \times 10^8 \) yr and \( k = 0.6 \), the values suggested by Gieles et al. (2006a), predicts significantly more curvature than is observed in the data.

Previous works reached a different conclusion regarding the disruption of clusters in M51 than we found here. We believe this is due to the fact that these works applied the indirect method developed by Boutloukos & Lamers (2003), which averages clusters over large ranges of mass and age and assumes that any bends observed in the mass and age distributions are due to mass-dependent disruption. However, bends can appear for other reasons, such as artifacts related to systematic errors or statistical noise, and are expected to appear in any case when the mass function is unrestricted in age (see Fall et al. 2009 for details).

When no bends or curvature are present in the mass function, only a lower limit can be determined for \( \tau_* \). We use the observed mass function and the predicted curves shown in the bottom panel of Figure 5 to estimate a lower limit for \( \tau_* \) of \( \approx 1 \times 10^9 \) yr, for an assumed value of \( k = 0.6 \). Higher values of \( k \) would lead to more curvature than shown for \( k = 0.6 \), and we find a lower limit of \( \approx 2 \times 10^9 \) yr for an assumed value of \( k = 1 \) (not shown). In summary, our results do not support previous suggestions of a characteristic disruption timescale \( \tau_* \approx 1–2 \times 10^9 \) yr for a typical \( 10^4 M_\odot \) cluster in M51.

5.3. Implications for the Galaxy-dependent Cluster Disruption Picture

We have just shown that the power-law shape observed for the mass function only allows us to place a lower limit on \( \tau_* \), i.e., that the mass-dependent disruption of clusters in M51 is not observed directly over the mass-age range probed here. This result is similar to those found previously for clusters in several different galaxies, including the Antennae, the LMC and SMC, M83 and M51. These galaxies span a factor of 100 in star formation rate, have different total masses and morphologies, and include spirals, dwarf irregulars, and merging galaxies. Together, they represent a good sample to assess whether or not there are strong variations in the rate of dynamical evolution of star clusters in different galaxies, at least for the first \( \approx \)“few” \( \times 10^8 \) yr. We have not found direct evidence in any of these systems that lower mass clusters are disrupted faster than higher mass clusters, although our observations are sensitive to different ranges in mass and age in each galaxy. Based on these results, we conclude that current observations do not support the notion that the disruption timescale \( \tau_* \) varies strongly for young clusters from galaxy to galaxy, and hence our results do not support the galaxy-dependent disruption picture. In a forthcoming paper, we will study the age distribution of clusters in M51 at different masses, and the mass function at different ages, to assess whether or not these support the “quasi-universal” picture for cluster disruption.

5.4. Ages of Clusters in Feathers

There are two interesting stellar features located within Region 1, and shown in Figure 6. These features, which we refer to as “feathers,” contain a number of star clusters, have larger pitch angles than the spiral arm and appear to be a continuation of dark extinction features (we refer to these extinction features as “spurs”). The spurs are also detected in CO (e.g., Corder et al. 2008; Koda et al. 2009), and appear to emanate from the outer (leading) portion of the spiral arm, suggesting that they are related in some way to both the spiral arm and the feathers. The spurs are also labeled in Figure 6.

Figure 7(a) shows that clusters brighter than \( M_V \lesssim 22 \) (\( M_V \lesssim -7 \); shown in red) located in feather 1 virtually all have the same age, and formed \( \approx 1 \times 10^8 \) yr ago. Most of the fainter clusters, with \( M_V \) between \(-6 \) and \(-7 \) (shown in blue), have similar estimated ages, although fainter clusters have larger uncertainties in their ages. We also note that the approximately 25th most massive, intermediate age star cluster in M51 is located within feather 1.

Figure 7(b) shows the locations and estimated ages for clusters brighter than \( M_V \lesssim -7 \) (shown in red) in feather 2.

\(^{12}\) We make similar assumptions here as the Gieles et al. works when estimating cluster masses and ages, namely a Salpeter IMF and a Galactic-type extinction law.

\(^{13}\) This assumption is consistent with the results found by Hwang & Lee (2010) for the mass function of \( \tau \lesssim 10^7 \) yr clusters in M51.
These clusters have similar but unidentical ages, with most forming $\tau \approx 2 \times 10^8$ yr ago. Fainter clusters, shown in blue, show a similar trend in their ages as the brighter clusters, although there are a handful of fainter clusters with significantly younger age estimates, where we believe our dating technique erroneously found a younger age and higher extinction than for the other clusters. When compared with their counterparts in feather 1, most clusters in feather 2 appear to be somewhat older, by a factor of $\approx 2$, and also to have formed over a longer period. The formal uncertainties in our age determinations for clusters in the feathers are only $\log (\tau/\text{yrs}) \approx 0.05$–0.1, supporting the idea of different ages for clusters in the two feathers. The age difference comes from a difference in the observed colors of the clusters. Over a similar magnitude range, clusters in feather 2 have a redder median $V-I$ color than clusters in feather 1 by $\approx 0.15$ mag, and also have a larger spread in $V-I$ color ($\sigma = 0.12$ versus $\sigma = 0.05$ for feather 1). We do not see evidence for age gradients along either feather, as might be expected if star formation had been triggered at one end and propagated across to the other end. In addition to forming earlier, feather 2 also has a larger pitch angle than feather 1.

The locations of $\approx 10^8$ Myr old clusters found here can help to distinguish between different scenarios for the excitation of spiral structure in M51. Based on a number of previous simulations, Dobbs & Pringle (2010) predict the locations of clusters with different ages from four mechanisms which can generate spiral structure: (1) a global, steady density wave; (2) a rotating, central bar; (3) local gravitational instabilities; and (4) strong, external tidal interaction. In these simulations, Dobbs & Pringle (2010) track the trajectory of the dense gas, and assume that these trajectories are not dissimilar to those of stars. Notional clusters with ages $\approx 10^8$ Myr are found primarily between spiral arms, including in feather-like structures with relatively large pitch angles, in the simulations for a global density wave and in a tidally induced spiral, but not for flocculent spirals. A central bar has not been observed in M51, implying that this model is also unlikely to explain spiral structure in M51, although the simulations do show intermediate-age clusters in feather-like features with appropriate pitch angles. We will make
a stronger test of how spiral structure is induced in M51, by comparing the locations of clusters of all ages younger than \( \approx \) few \( \times 10^8 \) yr across M51 with results from the Dobbs & Pringle (2010) simulations.

6. SUMMARY

We have used \( UBV \), \( H \alpha \) images taken with the ACS and WFPC2 cameras on board the \( HST \) to study star clusters in the nearby grand-design spiral galaxy M51. We estimated the masses and ages of the clusters by comparing the measured photometry with predictions from the population synthesis models of Bruzual & Charlot (2003; G. Bruzual 2007, private communication).

We constructed the mass function of intermediate-age (1–4 \( \times 10^8 \) yr) star clusters in a 3 \( \times 7 \) kpc\(^2\) region of M51, and found that it is well described by a single power law, \( dN/dM \propto M^\beta \), with \( \beta = -2.02 \pm 0.9 \), for \( M \gtrsim 6 \times 10^3 M_\odot \). This mass function is deeper by a factor of \( \approx 5 \) than those available in the literature. We also found \( \beta = -2.25 \pm 0.09 \) for the mass function of intermediate-age clusters across all of M51, but only down to masses of \( \approx 10^4 M_\odot \), due to the difficulty of selecting clusters in the crowded inner and spiral arm regions. This gives an average value of \( \beta = -2.1 \pm 0.2 \). The mass function does not have obvious bends at either the low or high mass end. We found that a power law provides a statistically acceptable fit to the mass function, based on quantitative tests, and does not require an upper mass cutoff. Therefore, we do not confirm previous suggestions that there is a cutoff of \( M_C \approx 2 \times 10^5 M_\odot \) for clusters in M51.

We also assessed previous suggestions for mass-dependent disruption of clusters in M51, where clusters are disrupted on timescales that depend on their mass as \( \tau_d(M) = \tau_s (M/M_\odot)^{k} \), with the specific values \( k = 0.6 \) and \( \tau_s = 2 \times 10^8 \) yr for a fiducial \( M_\odot \) cluster. These specific values predict a significant amount of curvature which is not observed in our mass function. We concluded that previous works reached an incorrect conclusion because they applied an indirect method which makes the a priori assumption that clusters are disrupted in a manner that depends on their initial mass, to lower quality observations with poorer spatial coverage taken with \( HST \)/WFPC2. The deeper observations presented here, which cover M51 nearly in its entirety, did not show evidence that lower mass clusters are disrupted earlier than higher mass cluster in M51, at least over the studied range of masses and ages.

Our results for the mass function of star clusters in M51 are similar to those found recently for \( \tau \lesssim \) few \( \times 10^8 \) yr cluster systems in several other galaxies, including the Magellanic Clouds, M83, and the Antennae, where we also did not find evidence for mass-dependent disruption. In light of these results, we concluded that there is currently no clear observational support for the suggestion that young clusters in different galaxies disrupt on very different timescales and in a mass-dependent fashion.

We also studied the ages of clusters in two prominent “feathers” located in Region 1, stellar structures beyond the inner spiral arm, which have a larger pitch angle than the arms. The clusters located within one feather appear to have formed coevally, approximately \( 1 \times 10^8 \) yr ago, while clusters in the second feather formed earlier, with a typical age of \( 2 \times 10^8 \) yr, but over a longer period. We compared the locations of \( \approx 10^8 \) yr clusters in M51 with predictions from Dobbs & Pringle (2010), and ruled out a scenario where self-gravity of the stellar disk is responsible for generating the spiral structure in M51.

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REFERENCES

Bastian, N., Gieles, M., Lamers, H. J. G. L. M., Scheepmaker, R. A., & de Grijs, R. 2005, A&A, 431, 905
Bik, A., Lamers, H. J. G. L. M., Bastian, N., Panagia, N., & Romaniello, M. 2003, A&A, 397, 473
Boutloukos, S. G., & Lamers, H. J. G. L. M. 2003, MNRAS, 338, 717
Bresolin, F., & Kennicutt, R. C. 2002, ApJ, 572, 838
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Burkert, A., & Smith, G. H. 2000, ApJ, 542, 95
Calzetti, D., Chandar, R., Lee, J. C., Elmegreen, B. G., Kennicutt, R. C., & Whitmore, B. C. 2010, ApJ, 719, L158
Chabrier, G. 2003, PASP, 115, 763
Chandar, R., Fall, S. M., & Whitmore, B. C. 2010a, ApJ, 711, 1263
Chandar, R., et al. 2010b, ApJ, 719, 966 (M83)
Corder, S., Sheth, K., Scoville, N. Z., Koda, J., Vogel, S. N., & Ostriker, E. 2008, ApJ, 689, 148
de Grijs, R., & Anders, P. 2006, MNRAS, 366, 295
Dobbs, C. L., & Pringle, J. E. 2010, MNRAS, 409, 396
Dolphin, A. 2000, PASP, 112, 1397
Fall, S. M., Chandar, R., & Whitmore, B. C. 2005, ApJ, 631, L133 (FCW05)
Fall, S. M., Chandar, R., & Whitmore, B. C. 2009, ApJ, 704, 453 (FCW09)
Fall, S. M., & Zhang, Q. 2001, ApJ, 561, 751
Feldmeier, J. J., Ciardullo, R., & Jacoby, G. H. 1997, ApJ, 479, 231
Fitzpatrick, E. L. 1999, PASP, 111, 63
Gieles, M. 2009, MNRAS, 394, 2113
Gieles, M., Bastian, N., Lamers, H. J. G. L. M., & Mout, J. N. 2005, A&A, 441, 949
Gieles, M., Larsen, S. S., Scheepmaker, R. A., Bastian, N., Haas, M. R., & Lamers, H. J. G. L. M. 2006a, A&A, 446, L9
Gieles, M., Portegies Zwart, S. F., Baumgardt, H., Athanassoula, E., Lamers, H. J. G. L. M., Sipior, M., & Leenaarts, J. 2006b, MNRAS, 371, 795
Holzman, J. A., Burrows, C. J., Casertano, S., Hester, J. J., Trager, J. T., Watson, A. M., & Worthey, G. 1995, PASP, 107, 1065
Hwang, N., & Lee, M. G. 2010, ApJ, 709, 411
Jordan, A., et al. 2007, ApJS, 171, 101
King, I. 1966, AJ, 71, 64
Koda, J., et al. 2009, ApJ, 700, L132
Lamers, H. J. G. L. M., Gieles, M., & Portegies Zwart, S. F. 2005, A&A, 429, 173
Larsen, S. S. 1999, A&AS, 139, 393
Lundgren, A. A., Wiklind, T., Olofsson, H., & Rydbeck, G. 2003, A&A, 413, 505
Maiz Apellaniz, J., & Ubeda, L. 2005, ApJ, 629, 873
Moustakas, J., Kennicutt, R. C., Tremonti, C. A., Dale, D. A., Smith, J. D. T., & Calzetti, D. 2010, ApJS, 190, 233
Portegies Zwart, S., McMillan, S., & Gieles, M. 2010, ARA&A, 48, 431
Salpeter, E. 1955, ApJ, 121, 161
Schuster, K. F., Kramer, C., Hitschfeld, M., Garcia-Burillo, S., & Mookerjea, B. 2007, A&A, 461, 143
Sirianni, M., et al. 2005, PASP, 117, 1049
Whitmore, B. C., Chandar, R., & Fall, S. M. 2007, AJ, 133, 1067
Whitmore, B. C., et al. 2010, AJ, 140, 75

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