Starbursts and Star Clusters in the Ultraviolet

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ABSTRACT

We present ultraviolet (UV) images of nine starburst galaxies obtained with the Hubble Space Telescope using the Faint Object Camera. The galaxies range in morphology from blue compact dwarfs to ultra-luminous merging far-infrared galaxies. Our data combined with new and archival UV spectroscopy and far-infrared fluxes allow us to dissect the anatomy of starbursts in terms of the distributions of stars, star clusters and dust.

The overall morphology of starbursts is highly irregular, even after excluding compact sources (clusters and resolved stars). The irregularity is seen both in the isophotes and the surface brightness profiles. In most cases the latter can not be characterized by either exponential or $R^{0.25}$ profiles. Most (7/9) starbursts are found to have similar intrinsic effective surface brightnesses, suggesting that a negative feedback mechanism is setting an upper limit to the star formation rate per unit area. Assuming a continuous star formation rate and a Salpeter (1955) IMF slope, this surface brightness corresponds to an areal star formation rate of $0.7 M_\odot Kpc^{-2} yr^{-1}$ in stars in the mass range of $5 - 100 M_\odot$.

All starbursts in our sample contain UV bright star clusters indicating that cluster formation is an important mode of star formation in starbursts. On average about 20% of the UV luminosity comes from these clusters. The clusters with $M_{220} < -14$ mag, or super star clusters (SSC) are preferentially found at the very heart of starbursts; over 90% of the SSCs are found where the underlying surface brightness is within 1.5 mag arcsec$^{-2}$ of its peak value. The size of the SSCs in the nearest host galaxies are consistent with those of Galactic globular clusters. Our size estimates of more distant SSCs are likely to be contaminated by neighboring clusters and the underlying peaked high surface brightness background. The luminosity function of SSCs is well represented by a power law ($\phi(L) \propto L^\alpha$) with a slope $\alpha \approx -2$.

We find a strong correlation between the far infrared excess and the UV spectral slope for our sample and other starbursts with archival data. The correlation is in the sense that as the UV color becomes redder, more far-infrared flux is observed relative to the UV flux. The correlation is well modeled by a geometry where much of their dust is in a foreground screen near to the starburst, but not by a geometry of well mixed stars and dust. Some starbursts have noticeable dust lanes, or completely obscured ionizing sources, indicating that the foreground screen is not uniform but must have some patchiness. Nevertheless, the reddened UV colors observed even in these cases indicates that the foreground screen has a high covering factor and can account for a significant fraction of the far-infrared flux.
1. Introduction

Starburst galaxies are currently forming stars at a much higher rate than the past average. In the most extreme cases the star formation rate (SFR) is the highest permissible (i.e. SFR $\approx$ gas mass/dynamical time scale; Heckman, 1994). The intrinsic optical signatures of a starburst are a high surface brightness and a spectrum dominated by strong, narrow, high-excitation emission lines, a relatively weak continuum that is flat or rising bluewards and weak absorption features (primarily Balmer series). These signatures are often diminished by dust extinction. An important subclass of starburst galaxies are the far infrared galaxies (FIRGs; Soifer et al. 1987; Armus et al. 1990, hereafter AHM). These are very dusty systems in which the dust grains act to redistribute the intrinsic spectrum from the ultraviolet (henceforth UV) and optical to the far infrared, where most of the bolometric luminosity is emitted. Galaxies with starburst characteristics range in morphology from blue compact dwarfs (BCDs; Thuan & Martin 1981) to merging systems. The starburst itself is often confined to a small portion of a galaxy, frequently just the very central regions of a large spiral in which case they are classified as starburst nuclei galaxies (Balzano, 1983). Spectacular galactic winds are often observed in starburst galaxies ranging in luminosity from BCDs (e.g. Meurer et al. 1992, hereafter MFDC; Marlowe et al. 1995) to ultraluminous FIRGs (AHM; Heckman et al. 1990).

High mass stars ($m_\ast > 10M_\odot$) especially the hottest, are the driving engines of starbursts. Ultimately, they provide most of the luminosity, are responsible for ionizing the ISM and warming the dust, and through their stellar winds and supernovae power the galactic winds. Although much of what we know about starbursts is from optical and infrared observations, it is the UV where these stars directly dominate the spectral energy distribution.

Numerous spectroscopic studies of starbursts using the *International Ultraviolet Explorer* (IUE) have been published. Recently, Kinney et al. (1993, hereafter K93) presented an atlas of IUE spectra of 143 star forming galaxies, many of them starbursts. UV imaging studies of galaxies are somewhat rarer. Most previous studies have been obtained either from balloon-born experiments such as FOCA (e.g. Buat et al. 1994; Reichen et al. 1994; Courvoisier et al. 1990; Donas et al. 1987) or limited duration space flights such as FAUST (Deharveng et al. 1994) and UIT (e.g. Hill et al. 1992; Chen et al. 1992). Mostly “normal” galaxies were observed by these experiments, at angular resolutions of $\sim 4^\prime$ to $\sim 3.5^\prime$. With the launch of the *Hubble Space Telescope* (HST) we can now obtain UV images at $\sim 50$ mas (milli-arcsecond) resolution, or physical sizes of $\sim 2$ pc at a distance of 10 Mpc. Thus we now have the capability of determining the detailed structure or “anatomy” of a starburst at a wavelength near where the hot high mass stars dominate. This is the next best thing to seeing the intrinsic distribution of ionizing radiation ($\lambda < 912\AA$), which of course is impossible since very little of it escapes the starburst’s ISM.

In this paper we examine the UV anatomy of nine starburst galaxies imaged by HST. The UV observation yield important results concerning the distributions of star formation and dust in starbursts. The selection of the sample and data reduction and analysis are discussed in §2. The properties our observations are sensitive to and the morphology of each galaxy is discussed in §3. The global properties of the galaxies (e.g. integrated fluxes, spectral slopes, mean surface brightness) are presented in §4. These are heavily affected by dust. The combination of UV and far-infrared photometry and UV spectroscopy provide strong constraints on the dust distrubution. These are discussed in §4.1. The properties after dehrouding the dust distribution are presented in §4.2. To derive physical properties such as mass, and reddening, we compare UV properties with stellar population
models which are derived from the models of Leitherer & Heckman (1995; hereafter LH) and Bruzual & Charlot (1993). These models are presented in the appendix.

The sample galaxies all contain UV bright compact objects. We identify the brightest of these as star clusters. Cluster formation is an ongoing process in star forming galaxies as near as the LMC. High luminosity “super” star clusters (SSCs) have been identified from the ground in the BCD/amorphous galaxies NGC 1569 (Arp & Sandage 1985) and NGC 1705 (Melnick et al. 1985; MFDC). With the launch of HST, SSCs are being discovered more frequently in such galaxies as the amorphous galaxy NGC 1140 (Hunter et al. 1994), the Wolf-Rayet galaxy He2-10 (Conti & Vacca 1994), the peculiar galaxy NGC 1275 (Holtzman et al. 1992), the merging systems NGC 7252 (Whitmore et al. 1993) and NGC 4038/4039 (Whitmore & Schweizer, 1995; hereafter WS), and within the circumnuclear starburst rings around the Seyfert galaxies NGC 1097 and NGC 6951 (Barth et al. 1995). These galaxies can also be classified as starbursts, or as containing starbursts. So one of our most important conclusions is that cluster formation is an important mode of star formation in starburst galaxies. In §5 we examine the nature of the clusters. In particular we consider their location within the starbursts, we estimate their sizes, and derive a luminosity function.

In §6 we summarize our results and what they tell us about the anatomy of starbursts.

2. The Observations

2.1. Sample selection

Our sample was selected from the K93 IUE atlas. The main selection criterion was UV brightness. Since the K93 fluxes are limited by the \( \sim 10'' \times 20'' \) IUE aperture, this translates to a lower limit on the UV surface brightness within this aperture. The final sample was selected to cover a wide range of metallicity and luminosity, and to have low foreground extinction. Table I summarizes much of what was previously known about the sample from optical observations. The properties include distance, \( D \), determined from the radial velocity, \( V_r \), after a Virgocentric flow correction and assuming \( H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \) (except for NGC 5253 for which we adopt the Cepheid distance of Sandage et al., 1994), the absolute magnitude \( M_B \), and the morphology. See Table I for details on how these quantities were calculated and the sources of the data. Since we are primarily concerned with UV data it is important to parameterize the amount of extinction due to dust. Table II gives relevant estimates of reddening, \( E(B-V) \), and extinction \( A_{\lambda} \), both from the Milky Way foreground and internal to the sample galaxies. Reddening and the internal extinction are discussed in detail in §4.1.

The sample covers a wide range of starburst types from low luminosity, virtually dust free BCDs, such as IZw18, to dusty FIRGs in merging systems, like NGC 3690. Most of the starbursts are located near the center of the host galaxy. The clearest exception is NGC 3991, an Im galaxy with an off-center starburst. In addition, IZw18 is so irregular in the optical and radio that it is not clear where the dynamical center is (Dufour & Hester 1990). A detailed examination of the environment of the sample is beyond the scope of this paper. Nevertheless it is fair to say that many of the galaxies are in groups where the chances for interactions are high (e.g. NGC 3991, NGC 5253, NGC 7552, and especially NGC 3690) while others appear to be fairly isolated (e.g. NGC 1705).

2.2. Data Reduction and Analysis

Ten images of the nine sample galaxies were obtained with the Faint Object Camera (FOC) and the F220W filter (and neutral density filter, F1ND, as required). Due to a fortuitous scheduling error, two exposures of NGC 1705 were ob-
tained. The reduced images are reproduced in Fig. 1 (plates XXXX). Table 3 summarizes the observations. The positions correspond to some well defined object, usually a bright cluster, that we define as the coordinate system origin. They should be accurate to $\sim 0.7''$ which is the sum in quadrature of the $0.6''$ accuracy of the HST Guide Star Catalog (Lasker et al. 1990; Russell et al. 1990) and the error in the FOC aperture position of $0.24''$ (Hack & Nota 1994). However, no external verification of the astrometry has been made for our frames. The images were obtained in fine lock mode, before the refurbishment mission, thus they suffer from spherical aberration. The largest FOC format, $512 \times 1024$, was employed, yielding a $22'' \times 22''$ field, and rectangular pixels in the raw image. The initial data reduction, with the standard HST pipeline processing (Nota et al. 1993), includes dark-count subtraction, “de-zooming” the rectangular pixels by splitting the flux into two square pixels, calculating the quantities required for photometric calibration, removal of geometric distortions, and division by a heavily smoothed (by $\sim 15$ pixels) flatfield. The final pixel size is $22.5$ mas (Baxter 1993). Most further processing was done within IRAF, the Image Reduction and Analysis Facility.

Pixels in the cores of the brightest clusters in NGC 1705, NGC 3690, and NGC 7552 have raw data values that exceed the 8-bit word length of the full format images and thus “wrap around”. The NGC 3690 and NGC 7552 images were fixed by adding appropriate multiples of 256 to the affected pixels of the raw images and then re-running the pipeline calibration. This was not feasible for the NGC 1705 frames because of saturation near the center of its dominant cluster, NGC1705-1. They were not corrected.

The photometric calibration coefficients were adjusted for two effects. The first is, the slow deterioration with time of the detector quantum efficiency. We calculate a $\sim 3\%$ deterioration relative to the mean epoch of the calibration observations ($\sim 1990.9$; Sparks, 1991) from data obtained with the F210M filter by Greenfield et al., (1993). Secondly, the pipeline calibration observations employed the $512 \times 512$ format, while the $512 \times 1024$ format is actually more sensitive by $25\%$ (Greenfield 1994b). There is then a net $22\%$ increase in sensitivity for observations relative to the pipeline calibration.

The FOC is a photon counting device which has a nonlinear response to incident flux. Its linearity behavior depends on the source distribution. We corrected for the “flatfield”, or large scale length, component of non-linearity using the algorithm of Baxter (1994a), and the appropriate linearity parameter from Nota et al. (1993). The maximum correction factor was arbitrarily limited to 1.7. On average the linearity correction increases the total flux of our objects by $7\%$ (the range is $3\%$ to $14\%$). On smaller scales the correction is more important. For example at the center of NGC 7552 the mean correction factor is 1.5 in a central $25 \times 25$ box. Linearity corrections at this level are highly uncertain. However, since only a small portion of the galaxy is affected, the total flux is relatively well defined.

Baxter (1994a,b) finds that the additional non-linearity of point sources is negligible out to an integrated count rate of $C \sim 4.1$ Hz in a $5 \times 5$ aperture in frames that have been corrected for flatfield non-linearity. Only the brightest clusters (one or two objects per galaxy) in NGC 3310, NGC 3690, NGC 4670, NGC 7552, and Tol1924-416 are beyond this limit. The flux of NGC 1705-1 was not estimated from aperture photometry so is not affected by point-source non-linearity. Baxter (1994a,b) notes that the FOC zoomed modes appear to be $10\%$ less sensitive to point sources than to extended sources, in data that has been corrected for flatfield non-linearity.

The IUE spectra of K93 provide us with an excellent source to check our photometry as well as complimentary spectral information. In Fig. 2
We compare the FOC and IUE magnitudes of our sample. The $m_{220}$ magnitudes are on the “STMAG” system which is described in the appendix. $m_{220}$(FOC) was extracted using a circular aperture matching the area of the IUE extraction aperture of K93. $m_{220}$(IUE) was extracted using the IRAF package SYNPHOT to define the combined system throughput. Table 4 also presents the UV spectral slope $\beta$ ($f_\lambda(\lambda) \propto \lambda^\beta$) fitted to the IUE spectra using the continuum windows of Calzetti et al. 1994; hereafter C94). The redleak parameter $RL$ (defined in the appendix) was also extracted from the spectra, but was always found to be negligible, as expected ($|RL| \leq 0.03$ mag). Three of the galaxies have Faint Object Spectrograph (FOS) spectra available which were obtained with a 1″ aperture. These spectra are discussed fully by Robert et al. (1995). $\beta$ measured from these spectra are also presented in Table 4.

Figure 2 shows that the HST and IUE magnitudes agree very well except for NGC 3690, which forms with IC 694, the merging system Arp 299. K93 note “The IUE aperture contains both objects”. This is impossible since each is about 15″ in diameter with their centers separated by ~ 23″ (Wynn-Williams et al., 1991). The low IUE flux suggests that the IUE aperture was not centered on NGC 3690. The large disagreement between the IUE and FOS values of $\beta$ supports this view. The unweighted mean difference $\langle m_{220}(\text{FOC}) - m_{220}(\text{IUE}) \rangle = -0.05 \pm 0.05$ mag (after excluding NGC 3690) is slightly less than zero, perhaps due to the difficulty in centering the IUE aperture. The uncertainty is the standard error of the mean. The rms about the mean is 0.13, the same as the average error in the difference, indicating that random errors dominate the error in the mean.

A point spread function (PSF) is required at various stages in the analysis. We employ two empirical F220W PSFs in this study; one made available to us by D. Baxter, the other obtained directly from the HST data archive. Most of the data manipulation described below used the former PSF, while the latter was used primarily as a check. The PSFs were corrected for flatfield non-linearity. Neither perfectly matches the actual PSF of the images because of the effects of focus differences due to desorption in the optical telescope assembly and “breathing” as the HST makes a day-night transition (Baxter et al., 1993). In some images (those of NGC 1705, NGC 3690, NGC 4670, and Tol1924-416) rings around the brightest sources can clearly be detected. These are not intrinsic to the galaxy, but are the faint PSF wings of the bright source at their center. For these images the PSF was magnified to match the observed ring radii and then used in the image restoration described below. This is an appropriate procedure, since to first order a focus change contracts or expands the location of features in the PSF halo (Baxter et al. 1993). The magnification factors of 1.03 – 1.07 indicate focus changes of ~ 10µm.

Figure 1 shows that the sample galaxies contain numerous embedded compact sources. We have attempted to separate this clumpy structure and associated PSF halos from the smooth structure, in order to estimate their relative contributions to the total light. This was done by first restoring (deconvolving) the images using 25 standard iterations of the Richardson-Lucy algorithm (Richardson, 1972; Lucy, 1974). Point-like sources were found using the DAOFIND algorithm in IRAF’s implementation of the DAOPHOT package (Stetson, 1987). Note that the DAOPHOT package was not used to measure the magnitude of the sources, only to find them. The sources were then “zapped” (replaced with a fitted surface plus artificial noise) from the restored image. The resultant image was reconvolved with the PSF, and then smoothed with a 15 × 15 pixel median filter to yield the smooth image. The clumpy image is the difference between the original image and the smooth image.

The NGC 1705 images required special attention due to the saturated core of NGC1705-
1. We removed this source by modeling its strength from the wings of its radial profile (at \(0.45'' \leq r \leq 2.15''\)). NGC1705-1 was assumed to have an intrinsically circularly symmetric Gaussian profile with a full width at half maximum, \(W_{50} = 46\) mas. The model yields \(m_{220} = 12.72\) mag for NGC1705-1, to within 0.01 mag between the two frames. Since the core of the images have been excluded, this measurement is not affected by point source non-linearity. The model cluster was convolved with the PSF and subtracted from the images. The residuals in the core region were zapped. Figure 3a,b (plate XXXX) shows the central region of NGC 1705a frame before and after the removal of NGC1705-1. The smooth-clumpy separation was then performed on the images with NGC1705-1 removed.

Figure 4 schematically shows the results of the smooth–clumpy separation. The panels show the isophotes from the smooth images superimposed with the objects found by DAOFIND (and NGC1705-1). The symbol size indicates the magnitude of the objects as determined from aperture photometry of the linearity corrected images, using a circular aperture of radius \(r = 3\) pixels, with “sky” taken as the mode in an annulus of \(r = 4\) to 7 pixels. The aperture correction to total flux of this aperture is \(-2.26\) mag, as determined from both the primary and secondary PSFs. We adopt a final aperture correction of \(-2.36\) mag to account for the apparent decreased sensitivity to point sources discussed above.

Surface brightness, \(\mu\), profiles were extracted from each frame and are illustrated in Fig. 5. The extraction procedure was complicated because of the highly irregular morphology of the targets; many are club shaped, and typically the isophote centers, and shapes vary with isophote level. Our approach is to extract the mean number of counts in elliptical annuli and convert to \(\mu\). Bad areas (the distorted edges of the frame, the FOC occulting fingers and a bad scratch) are masked out of the analysis. The ellipse parameters are central coordinates, \(\Delta\alpha, \Delta\delta\) (relative to coordinates in Table 3); axial ratio, \(a/b\); and position angle, \(\phi\), which are a function of semimajor axis length, \(a\). We hold these parameters constant beyond some outer \(a = a_o\), and inwards of some inner \(a = a_i\). For \(a_i < a \leq a_o\) the parameters are set to vary linearly with \(a\) between the values at \(a_i\) and \(a_o\). The adopted ellipse parameters at \(a_i\) and \(a_o\) are given in Table 4. The parameters at \(a_o\), meant to be representative of the outer isophotes, were determined using a moment analysis technique (Meurer et al. 1994) applied to the smooth component images. The exceptions were NGC 5253 and NGC 3310. Due to their size, few complete isophotes are found; eye estimates of the parameters were used instead. At \(a_i\), the parameters are set to be circular, centered near the \(\Delta\alpha, \Delta\delta\) at \(a_i\) determined from the moment analysis. Circular parameters are adopted because PSF blurring tends to make the isophotes rounder towards the target centers, especially if they are highly concentrated. Often there is a bright compact source near the center determined from the moment analysis. In these cases \(\Delta\alpha_i, \Delta\delta_i\) were adjusted to coincide with this source.

The \(\mu\) profiles were extracted out to \(a_{max}\), where the surface brightness is twice the uncertainty in the background level. For NGC 3310, \(a_{max}\) is where less than half the area of the annulli are on un-masked portions of the frame. \(\mu\) profiles were extracted from both the total images and the smooth component images. The annuli widths were 50, and 350 mas, respectively. NGC 3690 shows three distinct “blobs” (see below) in the FOC images and the profiles of each of these were measured separately. Some properties of the targets extracted from the surface photometry are presented in Table 6. These properties include \(a_{max}; a_e\), the semi-major axis length containing half the light; \(m_T\), the total \(m_{220}\) found

\[4\]This is an early estimate of the cluster size determined from the PC images of O’Connell et al. (1994). A better estimate is given in §5.2.
by reintegrating the $\mu$ profile out to $a_{\text{max}}$; $\mu_e$, the surface brightness within $a_e$; and $f_{\text{clumpy}}$ the fraction of the flux coming from the clumpy image. These quantities are limited by the FOC field of view. In most cases the sources are fairly well contained within the detector field of view, although some have low surface brightness features extending beyond the frame (NGC 4670, NGC 3690, NGC 3991). Only in two cases, NGC 3310 and NGC 5253, do the UV distributions extend beyond the frame at high surface brightness. Except in these two cases, the background count rates of the frames are very similar, suggesting that “sky” and not diffuse emission from the host galaxies dominates the background.

3. UV morphology

3.1. What the observations are sensitive to

The optical spectra of the sample galaxies are all dominated by bright narrow emission lines, as are most of the galaxies in the K93 atlas. This indicates that they contain an ionizing population of stars. We assume it is this population, that is the stars formed at the same epoch, that dominate the FOC and IUE observations. This ionizing population assumption provides a strong constraint on the intrinsic UV properties of the sample, particularly on the UV spectral slope $\beta$ (appendix). As shown in the appendix, the F220W filter is well suited to observing high mass stars. For a Salpeter (1955) IMF, which we adopt, extending up to $m_u = 30 - 120 \, M_\odot$ and continuous star formation for 10 Myr, the median stellar mass our observations are sensitive to is $\sim 20 \, M_\odot$, and stars with $m_* \leq 5 \, M_\odot$ provide negligible flux. Although 20 $M_\odot$ stars contribute to the ionizing flux, the emission shortwards of 912 Å primarily originates in stars with $m_* \gtrsim 50 \, M_\odot$. Likewise, these most massive stars are individually the brightest in $M_{220}$ but are insufficient in number to contribute significantly to the integrated $M_{220}$. Nevertheless it is not unreasonable to assume that if ionizing stars are present, they and stars down to $\sim 20 \, M_\odot$ formed at the same epoch are what dominates our F220W observations.

Other factors affecting our F220W observations examined in the appendix include redleak and nebular continuum contamination. To summarize, the F220W filter does not suffer from significant redleak, especially when the source spectrum is young enough to ionize the ISM. Nebular continuum emission may contribute up to $\sim 30\%$ of the F220W flux. Dust can modulate the surface brightness distribution by absorption and by scattering UV photons into and out of the line of sight.

Figures 1 and 4 show that the starburst morphology in the UV is irregular. The diffuse light distribution has misshapen, non-elliptical isophotes. The surface brightness profiles (Fig. 5) are not well characterized by either exponential, (except, perhaps the smooth component of NGC 3690-Ab), or $R^{0.25}$ profiles. Instead, like the isophotes, the $\mu$ profiles are irregular (although one should bare in mind the small field of view).

Embedded in the diffuse light are numerous compact sources. These are clearly evident in Fig. 1. Those found in the course of the smooth-clumpy separation are indicated in Fig. 4. Here the nomenclature uses the galaxy’s name as the prefix, and the ranking of the source in $M_{220}$ as the suffix. Table 7 presents a cross-identification of the compact sources previously identified in the literature. In §5.2 we tabulate properties of some of the sources, including the relative positions of all sources mentioned below.

The peak brightness of a 100$M_\odot$ star is $M_{220} = -10.7$. Sources much brighter than this are not likely to be single stars. We show in §7 that many of the sources are significantly brighter than this and have sizes that are consistent with being star clusters. We define the term “s
per star cluster” (SSC) to denote clusters with $M_{220} < -14$ (this corresponds to $M_V < -13$ for 10 Myr old clusters; for other ages see the appendix). These must contain at least 20 high luminosity stars, and thus can not be confused with small multiple star systems.

3.2. The gallery

The following discussion of each galaxy’s UV morphology and relevant previous work is arranged by distance. East, north offsets (relative to the coordinates in Table 3) of objects in arc- seconds are given in $\pm$E.E,$\pm$N.N format.

NGC 5253: This nearest galaxy in our sample is certainly the Rosetta stone. It is near enough to resolve into stars, and to spatially resolve most of the clusters. Without the high spatial resolution of the HST it is hard to differentiate between clusters and stars. In the detailed optical study of Caldwell & Phillips (1989) many of the point like sources are incorrectly referred to as clusters. It took the planetary camera (PC) images presented by Sandage et al. (1994) and Saha et al. (1995) to demonstrate that NGC 5253 is resolved and that some of the sources are Cepheid variables. In the optical, the high surface brightness blue central region is where the emission line strength is most intense (Walsh and Roy 1987; 1989). We image only part of this region; UV emission clearly extends beyond the edge of the frame, particularly towards the south. NGC 5253 illustrates the basic UV morphology of a starburst: stars are distributed like the diffuse light, while clusters (in this case easily distinguished by their fuzzy appearance) are preferentially found near the center of the burst. Of the objects listed by Caldwell & Phillips only the five nuclear knots are in our frame. Our identifications of them are listed in Table 7. We do not see their knot 5. Comparison with PC images (Saha, 1994, private communication) suggests that it is an emission line knot. Walsh & Roy (1987, 1989) find an enhanced nitrogen abundance and a Wolf-Rayet spectrum in their spectral cube centered near NGC5253-1. Comparison with an $R$ frame (kindly made available to us by M. Lehnert) indicates that this cluster is the bluest of the nuclear knots, as well as the brightest in the UV. We tentatively identify it as the Wolf-Rayet cluster, indicating its age is $t \approx 3 - 8$ Myr (LH). This object itself is resolving into stars. A well known dust lane causes the indentation in the isophotes to the SE of NGC5253-1. From the low detected star density (Fig. 4) we infer that it cuts through the center of NGC 5253, passing $\sim 2''$ to the south of NGC5253-1. It is the continuation into the center of NGC 5253 of the [O III] filament discussed by Graham (1981). NGC 5253 is a member of the Cen A group.

NGC 1705: NGC 1705 is close enough to resolve into stars. It is the nearest galaxy in our sample that contains a SSC, and a spectacular one at that: the third brightest in our sample if we exclude those in the highly reddened galaxies NGC 3690 and NGC 7552. It is discussed at great length by MFDC and Meurer (1989), who show that it is the likely power source of the spectacular galactic wind seen in NGC 1705. They estimate its age as $t = 13$ Myr, which means it is no longer an ionizing source, yet it accounts for nearly half of the total $F_{220}$. At an age of 2 Myr it would have been about two magnitudes brighter (appendix). O’Connell et al. (1994) present HST PC images of NGC 1705 in the F555W and F785LP passbands from which we have estimated the $R_e$ of NGC1705-1 ($\S5.2$). After modeling and removing NGC1705-1 we see that the underlying UV distribution is still concentrated towards it, as can be seen by its surface brightness profile in Fig. 5. This suggests that the SSC may have more extended wings than our simple model of a circularly symmetric Gaussian, as would be expected for a cluster having a

5The $D = 4.7$ Mpc adopted by MFDC is in error due to a mistake in their code for deriving $D$ from $V_r$. 

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King (1966) or power law profile. The removal of NGC1705-1 allows NGC1705-2 to clearly be seen. This source is not seen in ground based images, but is mentioned by O'Connell et al. (1994). Protrusions in the the outer isophotes of NGC 1705 correspond to knots B and C of Melnick et al. (1985). There are a swarm of sources at knot B, the brightest H II region in the galaxy (MFDC). Some may be individual ionizing stars. The two UV frames are separated by 41 days. Are there any variable stars in NGC 1705? Typical random errors in $m_{220}$ from photon statistics are 0.1 mag, while additional spatial variations in the FOC performance will add another quasi-random error of 0.15 mag (Meurer, 1995a). Therefore the intrinsic uncertainty in $\Delta m_{220}$ is 0.25 mag. There are two sources which differ by $\geq 0.5$ mag between the two exposures: NGC1705-25 has $m_{220} = 19.7, 18.9$ in exposures a and b respectively; while NGC1705-17 has $m_{220} = 18.9, 19.5$. Neither are very convincing variable star candidates. In frame b, NGC1705-25 is at the edge of the region where the FOC 512 $\times$ 512 format is burnt into the detector, while all the sources in the vicinity of NGC1705-17 appear dimmer in frame b relative to a, suggesting a large local zero-point difference.

IZw18: With an oxygen abundance $O/H \approx 1/50$ of the solar value (Dufour et al. 1988), IZw18 is the most metal poor galaxy known. Kunth et al. (1994), using high resolution UV spectra obtained with the GHRS on board the HST, argue that the oxygen abundance in the neutral ISM is about 20 times lower than in the H II. However, this interpretation is very controversial (Pettini & Lipman 1995). Our image contains the two bright condensations, commonly referred to as the NW and SE knots, that are the usual targets of spectroscopic studies. Fainter structure discussed in detail by Dufour & Hester (1990) and Davidson et al. (1989) falls outside our image. The two knots are separated by $\sim 5.8''$ in our images. Despite being a prototypical BCD galaxy, both the peak $\mu_{220}$ and the $M_{220}$ of the brightest cluster are the faintest observed in our sample. We demonstrate in §4.1 that this is not due to dust extinction. Compact sources are seen in both knots; about three times more in the NW knot than SE knot. I Zw18 is resolving into stars at the detection limit of our deep image. A faint filament, $\sim 1.8''$ long, appears to emanate westwards from the SE knot and then curves to the NW.

NGC 4670: Recently Hunter et al. (1994b) presented a detailed H I and optical study of NGC 4670 which shows that high mass star formation is restricted to a single central starburst. Outside of the starburst, the galaxy has smooth elliptical isophotes in the optical. This is very similar to other (but lower luminosity) amorphous/BCD galaxies such as NGC 1705 and NGC 5253. Our image is centered on the central kidney shaped starburst with dimensions of $880 \times 470$ pc. It contains 10 SSCs and numerous fainter sources. Low surface brightness extensions, $\sim 100 - 200$ pc wide and suggestive of a bar, continue eastwards and westwards to the edges of the frame. A moderately bright cluster, NGC4670-21, is contained in the westwards extension. A faint diffuse (diameter $\sim 0.6'' = 60$ pc) UV source located at $-10.0, +3.9$ corresponds to a detached H II region seen in the images of Hunter et al. (1994b).

NGC 3310: We image the central portion of this well studied starburst spiral. Its structures in the optical continuum, Hα, infrared, and radio continuum (e.g. Balick & Heckman 1981; Telesco & Gatley 1984) are reasonably well correlated with the UV. They include a central ring with $r \approx 7'' = 610$ pc, a mildly active nucleus, and the “Jumbo” H II region of Balick & Heckman. The latter is known to contain Wolf-Rayet stars (Pastoriza et al. 1993) and is located where NGC 3310’s southern arm attaches to the central region. These features are seen in our image, although the jumbo H II region is not completely in the field of view. The SE rim of the ring clearly has a higher surface brightness than the ill de-
fined NW rim which is composed of two faint strands separated by \( \sim 5'' \). Overall the morphology is suggestive of tightly wound spiral arms instead of a ring (also noted by van der Kruit & de Bruyn, 1976). The outer NW strand defines the stellar ring of Balick and Heckman; the nucleus is near the center of this ring. However, the dynamical center is near the center of the ring defined using the inner NW strand (van der Kruit 1976; Grothues & Schmidt-Kaler, 1991). Several dust lanes cut through the ring, most noticeably at +4.1,–4.3 and +1.9,–6.2. The nucleus is resolved:

\[ W_{50} \approx 1.4'' = 120 \text{ pc} \] contains a peculiar right angle structure (dimensions 39 \( \times \) 46 pc; width \( \lesssim 9 \text{ pc} \)). The cluster distribution is like that in the AGN galaxies NGC 1097 and NGC 6951 (Barth et al., 1995): clusters are found along the starburst ring (including the Jumbo H\textsc{ii} region which contains at least six) but not interior to it.

**NGC 7552:** We image the center of this nearly face-on spiral that shows ring and bar like structures on several scales (Feinstein et al., 1990; Forbes et al. 1994a,b; hereafter F94a, F94b). The most relevant to us is the 9'' \( \times \) 7'' = 960 \( \times \) 670 pc nuclear ring at the inner Lindblad resonance. This is best seen at radio wavelengths and in Br\textsc{\g} emission, and optical and infrared color maps, but is difficult to detect in either optical or IR broad band images (F94a,b). Interior to this is a nuclear bar which shows up in 1 – 0 S(1) H\textsc{ii} emission (F94b). The nucleus itself is weak or absent at all wavelengths leading F94b to conclude that it is dormant. In the UV there are two emitting regions corresponding to two of the hot spots along the nuclear ring. The brightest is nearly circularly symmetric at moderate surface brightness levels, with an extension to the south at lower levels. It corresponds to the northern part of the radio knot A, the brightest H\textalpha hotspot, and the “blue break” in the optical images of F94a. In the UV its center divides into two bright clouds 70 pc and 140 pc in diameter, perhaps separated by a dust lane. The larger of the two has four of the brightest SSCs, NGC7552-1,3,4,5, scattered around its periphery and the smaller has NGC7552-2 at its center. There are numerous fainter clusters throughout the halo of this region, in particular a spray of sources 1'' – 3'' S of the brightest source. The sources closest to the expected position of the nucleus (at –2.8,–1.6) are NGC7552-13,25 and have a relatively inconspicuous \( M_{220} \approx -14 \). The other UV bright region (–5.0,–2.1) corresponds to radio knot C of F94a. It contains four clusters. Much of the UV morphology of NGC 7552 is probably dictated by location of holes in the distribution of dust. We know from the radio and Br\textsc{\g} rings that a starburst ring is present (F94a,b). But at the two brightest Br\textsc{\g} hotspots, (B and D in the notation of F94a), where the ionizing emission should be strongest, there is little UV emission. The hotspots seen in the UV are those with the lowest extinction measurements in F94b.

**Tol1924-416:** Bergvall’s (1985) detailed optical study of this galaxy shows it to be dominated by a central starburst \( \sim 1.8 \text{ Kpc} \) across, which is embedded in a low surface brightness host. The central complex has two peaks separated by \( \sim 540 \text{ pc} \) on an EW line. Iye et al. (1987) discuss the emission line kinematics in this region. Bergvall notes that there may be some broad band variability associated with Tol1924-416, but this has not been confirmed. The central complex has a footprint morphology (1.8 \( \times \) 1.0 Kpc). The eastern peak of Bergvall clearly corresponds to Tol1924-416-1, one of the brightest SSCs in our sample. There are several diffuse sources associated with the western peak. A LSB knotty plume, 890 pc long, is seen extending from the heel to \( \phi \approx 210^\circ \). There are at least three isolated sources. The brightest, Tol1924-416-2, is double (companion Tol1924-416-12) and clearly seen in ground based images. It may have faint H\textalpha emission associated with it (Bergvall, 1985) suggesting that it is in the starburst and not a foreground star.
NGC 3690: The merging system Arp 299, consisting of NGC 3690 and IC 694, is very well studied (e.g. Gehrz et al. 1983; Friedman et al. 1987; Joy et al. 1989; AHM; Wynn-Williams et al. 1991, Mazarella and Boroson, 1993). Our image centered on NGC 3690 is one of the more spectacular images in our sample. It shows three UV bright clouds. The largest we refer to as “BC” because it contains the sources B and C of Gehrz et al. (1983). The smaller clouds are “Ab” and “Aa” following the nomenclature of Mazarella & Boroson (1993). The three clouds have ∼ 60 SSCs scattered amongst them (see Table 7 for cross identification with previous work). BC, is shaped like a foot with dimensions of 2.4 × 1.5 Kpc. The bright Hα emission regions correspond to the double SSC NGC3690-5,8 in the “heel” and the numerous SSCs in the “toes” of this structure such as NGC3690-6,7,9,10 (Wynn-Williams et al. 1991). Stanford & Wood (1989) measure an H I column density of $N_{HI} = 3.1 \times 10^{21} \text{cm}^{-2}$ towards BC. Using the conversion factor of Burstein & Heiles (1978) this corresponds to $E(B - V) = 0.62$, in excellent agreement with $E(B - V)_{BD}$ (Table 2) but not $E(B - V)_{UV}$ derived below. The two detached clouds Ab (–7.4,–4.6) and Aa (–13.3,–3.7) are each more luminous ($M_{220} = -19.9, -19.6$ respectively) than the dwarf galaxies in our sample: NGC 1705, IZw18, and NGC 5253. However, the extinction correction is large, and long-slit spectroscopy indicates that the reddening is not uniform, and thus $M_{220}$ may be underestimated (Gehrz et al. 1983; Friedman et al. 1987; Mazarella & Boroson 1993). Ab and Aa are both highly concentrated towards two of the most luminous SSCs (NGC3690-4,3 respectively), and also contain other clusters. Inadvertently, Aa was occulted by the F/96 thin finger. There were two recent SNe in NGC 3690: SN1992bu (van Buren et al. 1994), and SN1993G (Treffers et al. 1993; Forti 1993). The position of the latter is outside our field of view, while there is nothing apparent within 2′′ of the published position (∼ +5.6,–8.0 in our coordinate system) of the former. This is not surprising since SN1992bu exploded over a year prior to our observation.

NGC 3991: This outlying member of the NGC 3991/4/5 group (Garcia, 1993) is composed of two clumpy star forming complexes, aligned along either side of a faint nucleus (Keel et al. 1985). The northern complex is clearly the brighter of the two, and is all that is contained in our image. It has a bent peanut morphology (similar to IZw18) with a bright (northern most) and faint component separated by 1.9 Kpc. The faint component is partially occulted by the F/96 wide finger. NGC 3991 contains about two dozen clusters. A faint thin (∼ 0.1″ = 22 pc wide) filament 830 pc long apparently is directed towards (or from) the elongated source NGC3991-8.

4. Integrated properties

4.1. Spectral slope and UV extinction.

One of the biggest obstacles to interpreting UV observations is dust. It scatters and absorbs UV radiation much more efficiently than optical/IR radiation. The scattering can be both into and out of the line of sight. The net amount of light removed from the line of sight as a function of wavelength, the extinction law, depends critically on both the geometry of the dust distribution and the dust composition. Dust sufficiently close to a starburst will reradiate the light it absorbs in the far infrared. Thus the observed ratio of far infrared to UV emission, the far infrared excess, is a diagnostic of the redistribution of the spectral energy by warm dust. The spectral slope or color is a strong diagnostic of the dust geometry. If the dust distribution is inhomogeneous, or the dust is mixed in with the stars, the transmitted UV spectrum will be weighted towards the least extincted lines of sight; consequently the spectrum will be bluer than if the dust were in a foreground screen (Witt et al. 1992).

Figure 6 shows $\text{IRX} \equiv \log(\text{FIR}/F_{220})$ plotted...
against the UV spectral slope, $\beta$ ($f_\lambda \propto \lambda^\beta$) for starburst galaxies. Here, FIR is derived from 60$\mu$m and 100$\mu$m IRAS observations following the the definition of Helou et al. (1988). $F_{220}$ is the F220W UV flux ($\lambda f_\lambda$, as defined in the appendix), corrected for Galactic extinction (see Table 2), but not the internal extinction associated with the starburst. The data from our sample are supplemented with the remainder of galaxies in the K93 catalog which have IRAS fluxes. The fluxes for our program galaxies are reported in Table 3.

The strong correlation in Fig. 6 is in the sense that the redder $\beta$ is, the higher $F_{\text{IR}}$ is relative to $F_{220}$. This is exactly what is expected for reddening by a foreground screen of dust, as we show below. The horizontal bars in Fig. 6 show the range of intrinsic $\beta$ expected for ionizing stellar populations, $\beta_0 = -2.5 \pm 0.2$ (appendix). This is the a priori expected $\beta_0$ under the ionizing population assumption, and effectively the lower limit to the observed values of $\beta$; the majority of the galaxies have redder $\beta$, as would be expected if they were reddened by intervening dust. Calzetti et al. (1995) find a similar correlation between $\beta$ and log($L_{\text{IR}}/L_B$). Further evidence that the UV slopes are reddened is presented in Fig. 7 (and Fig. 12 of C94) which shows that $\beta$ correlates with the reddening derived from the Balmer decrement, $E(B-V)_{\text{BD}}$ (tabulated in Table 2). The two bluest galaxies in our sample, NGC 1705, and I Zw18 have $\beta = -2.5$, so they are virtually unreddened. Both galaxies also have a very low $F_{\text{IR}}$, suggesting a low dust content. I Zw18 is undetected by IRAS, while MFDC estimate $E(B-V) \leq 0.01$ for NGC 1705 from $F_{\text{IR}}$, assuming a foreground screen geometry for the dust.

Figure 6 provides constraints on the dust distribution and extinction law applicable to starburst galaxies. The dust has to be in the environment of the starburst (i.e. not in our Galaxy or the intergalactic medium) otherwise the dust would not be heated and IRX would be low for all sources. The large range of observed $\beta$ rules out a grey extinction law, or extinction only by UV opaque clouds of dust (or “bricks”), since in those cases we expect all galaxies to have $\beta = \beta_0 \approx -2.5$. It is also unlikely that the dust is evenly distributed and purely internal to the UV emitting region. In that case the UV emission and spectral slope will be dominated by stars within one optical depth of the “front” of the starburst and $\beta$ will asymptote to a constant value for high dust content. C94 model this geometry and find that the maximum increase in $\beta$ is 0.6, and 1.05 for Milky Way and LMC extinction laws, respectively. The starbursts with $\beta > -1.2$ can not be explained with this geometry, nor can the good correlation between $\beta$ and IRX.

Figure 6 shows the expected correlations for models where the dust is in a uniform foreground screen and the extincted radiation from A912 to $\lambda 8000$ is reradiated in the far infrared. We assume that 71% of this flux will be intercepted by the $F_{\text{IR}}$ “passband”. This is appropriate for dust at $T \approx 40-80$ K and a dust emissivity $\propto \nu$ (Helou et al. 1988). The source spectrum is assumed to be the total stellar plus nebular spectrum of a 10 Myr old constant star formation rate population (solar metallicity, Salpeter IMF) from the models of LH, and has $\beta_0 = -2.5$. Four reddening laws are considered: the Galactic reddening law of Seaton (1979), the LMC reddening law of Howarth (1983), and the starburst extinction laws of Kinney et al. (1994; hereafter K94) and C94. The appendix parameterizes the F220W extinction, $A_{220}$, and reddening of $\beta$, as a function of $E(B-V)$ for these reddening laws. Here we assume that the UV “aperture” (i.e. the extraction aperture of K93, or the FOC frame) recovers most of $F_{220}$, so that dust scatters equal amounts of flux into and out of the integrated line of sight. In other words, the absorption law is the extinction law. This is consistent with how the C94 and K94 extinction laws were derived, although not how the Galactic and LMC laws

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were derived. If a source spectrum with different $\beta_0$ is adopted, the primary effect on Fig. 6 is to shift the theoretical curves horizontally, with very little change in the shape of the curves, at least for ionizing populations. The LMC, C94 and K94 extinction models follow the observed correlation very well considering the simplicity of the models.

The importance of Fig. 6 is that it demonstrates that at least some of the UV to IR redistribution of light is due to foreground dust in close proximity to the starburst. How close must the dust be? We calculate a rough estimate as follows. The models of Désert et al. (1990) predict a tight relationship between the ratio of luminosity, the radius of a source spectrum is a power law with $\langle U \rangle < L_{50}$, and the UV energy density, $U$:

$$\log\left(\frac{f_\nu(60)}{f_\nu(100)}\right) = -0.48 + 0.30 \log U,$$

where $U$ is given in eV cm$^{-3}$, and the above relationship is good for $\log U < 3$, and calibrated for O5 and B3 stars. For an unattenuated point source $U = L_{\text{UV}}/(4\pi R^2 c)$. The IUE sample of starbursts has $\langle \log(f_{60}/f_{100}) \rangle = -0.17$. Adopting this mean, and assuming that the intrinsic spectrum is a power law with $\beta_0 = -2.5$ and $L_{\text{UV}}$ is the integrated flux from 912Å to 3000Å, then in terms of the F220W luminosity, the radius of the dust shell is

$$R_{\text{Dust}} \approx 190 \sqrt{\frac{L_{220}}{10^{42} \text{erg s}^{-1}}} \text{pc}.$$  

For the luminosity range of the FOC sample $0.3 < L_{220}/(10^{42} \text{erg s}^{-1}) < 90$ we have $0.1 < R_{\text{Dust}}/(\text{Kpc}) < 1.8$. We find a median $R_{\text{Dust}}/R_e = 2.5$. Thus in this model most of the dust is significantly beyond the effective radius, but still fairly close to the starburst.

Up until at least a decade ago, a foreground screen geometry for the dust was the standard implicit assumption of most astronomers. However, this geometry has been gradually rejected as being too simplistic. Weedman (1988, 1991) noted that UV selected galaxies had far IR properties similar to those selected for their far IR strength. For galaxies to be both UV and IR bright suggests that we are preferentially seeing galaxies through unobstructed lines of sight. Following up on this notion Witt et al. (1992) explored radiative transfer through a variety of geometries more complicated than a simple foreground screen. They note that “the screen geometry leads to a phenomenon that is simultaneously both widely believed and implausible: reddening of broad band color is positively correlated with increasing dust extinction.” Figure 6 shows exactly that phenomenon. How can this be?

First of all, a foreground screen geometry may not be so implausible after-all. The central region of a starburst is not likely to be a hospitable environment for dust, except in dense molecular clouds which will have a low volume filling factor. The Galactic winds frequently observed in starbursts will sweep out any diffuse ISM from the immediate environs of the starburst on the timescale of a few Myr (Heckman et al. 1990). A cavity around the starburst will form filled with a hot plasma of thermalized SNR having $T \sim 10^7 - 10^8$ K. Within the cavity there may be some molecular clouds compressed to high density and low volume filling factor by the hot plasma. As these evaporate they may release dust into the cavity. However, assuming a typical particle density of $n = 0.1 \text{cm}^{-3}$ in the cavity the timescale for destruction by sputtering is $\sim 5$ Myr for grains having a relatively large size of 0.25μm (Draine and Salpeter, 1979). Thus dust will be destroyed on a timescale equivalent to the time required to transport it from the core and somewhat less than the star formation timescale (see below). Much of the dust may be in the shell swept up by the Galactic wind. This shell would make an ideal foreground screen being roughly uniform until it fragments. In addition, part of the foreground dust may be in relatively undisturbed ISM remaining outside the starburst. We
would expect this ISM to be from the portion of the starburst’s nascent cloud not involved with star formation, and perhaps “fresh” ISM flowing in to “feed” the starburst.

Second of all, it is clear that a homogeneous foreground screen is not the whole story. There is plenty of evidence for some of the dust to be clumped, or patchy. Figure 7 shows the K94 reddening vector in the \(\beta, E(B-V)_{BD}\) plane assuming an intrinsic \(\beta_0 = -2.5\) and assuming \(E(B-V)_{UV} = E(B-V)_{BD}\), as we would expect for a uniform screen dust geometry. The correlation is significantly shallower than this vector. This is a well known phenomena: the Balmer decrement overpredicts the UV extinction (Fanelli et al. 1988; C94). It indicates that in starburst galaxies the H II has a different distribution relative to the dust than the UV. Thus a uniform foreground screen geometry is not totally adequate. For our sample the most discrepant points from the K94 line in Figs. 6,7 are NGC 3690 and NGC 7552. From NGC 7552 we are seeing only a fraction of the UV flux of the starburst ring of F94a, F94b as explained in §3.2. In this case the UV morphology is dictated by the location of holes in the dust distribution. It is then no surprise that \(\beta\) is steeper for the FOS spectrum, centered on the UV surface brightness peak, probably where the dust coverage is thinnest, than the IUE spectrum which includes the more extincted “edges” of the hole (Table 3). In NGC 3690, Gehrz et al. (1983) detect a strong 11.4 \(\mu m\) silicate feature indicating that much of the mid-infrared flux is due to features extincted by 5 to 14 magnitudes in the visual. The optical and UV data suggest extinctions of only 2 mag. Indeed, NGC 3690 is one of the most discrepant points in Fig. 6, in the sense we would expect if some of the UV sources are completely obscured. Dust lanes seen in our images of NGC 5253, NGC 3310 and NGC7552,

\footnote{So in this case the foreground screen is not the whole story but instead the \textit{hole} story!} further demonstrate that the dust distribution is not uniform in starbursts.

The dust distribution is thus not easily categorized. Although patchiness is directly observed in many cases, a significant fraction of the dust must be in a foreground screen. This is even true where the evidence for patchiness is greatest, NGC7552 and NGC 3690, otherwise they would not appear reddened. Since a foreground screen geometry adequately models the IRX - \(\beta\) correlation over large apertures, we can use this model to estimate the total UV fluxes from the measured fluxes and \(\beta\). This model is not sufficient to estimate either the total dust content or the local extinction. Nevertheless, out of a lack of a better solution, at present, we will adopt a uniform extinction for each galaxy.

For the remainder of the paper we adopt the starburst UV extinction law of K94 to derive the internal extinction. It is very similar to the LMC extinction law of Howarth (1983). This is appealing because the Howarth law does not in fact work for all of the LMC, but instead is applicable only to a \(~500\) pc region surrounding 30 Dor (Fitzpatrick, 1985), the nearest starburst to us. The main difference between the Howarth and K94 laws is the lack of the \(\lambda 2175\) \(\AA\) bump in the K94 law. Figure 6 shows that this law underpredicts IRX for a given \(\beta > -1\). This is consistent with additional patchiness in the dust distribution.

Here, the internal color excess is taken to be \(E(B-V)_{UV} = (\beta - \beta_0)/8.067\) (appendix), with \(\beta_0 = -2.5\), as expected for ionizing populations. As discussed in the appendix, a wide range of star formation histories, from short bursts less than 10 Myr old to continuous star forming regions 100 Myr and older will produce a spectrum with very similar \(\beta_0\). The range in \(\beta_0\) of \(\pm 0.2\) for ionizing populations amounts to an uncertainty in \(E(B-V)_{UV}\) of \(\pm 0.025\) mag, and in \(A_{220}\) of \(\pm 0.21\) mag. The adopted internal color excesses \(E(B-V)_{UV}\) and \(E(\beta) = \beta - \beta_0\) are given in Ta-
ble extinction along with the consequent total (Galactic + internal) extinction, $A_{220,T}$. For these calculations we use the $\beta$ values corrected for Galactic extinction given in Table 4. These are the IUE values except for NGC 3690, where the IUE aperture is probably not centered on NGC 3690 (§2.2). For it we use the FOS $\beta$.

### 4.2. Intrinsic properties.

Table 3 presents some integrated intrinsic (i.e. extinction corrected as discussed above) properties of the sample. The radii $R_e$ and $R_{\text{max}}$ are mean radii derived from $a_e$ and $a_{\text{max}}$ using

$$R = \sqrt{ab}.$$ 

The UV half light radii of the starbursts are in the range $100 \leq R_e \leq 700$ pc with the exception of NGC 1705. This is because NGC1705-1 contains nearly half the total flux of the galaxy. Since its size is not apparent from the UV observations, we report two cases: (1) it is assumed to be a point source (2) NGC 1705 in the absence of NGC1705-1. The size range of our sample is somewhat smaller than that of FIRGs, the largest of which have $R_e \sim 2$ Kpc (AHM). This may be in part because we resolve one of the largest starbursts in our sample, NGC 3690, into subcomponents.

The next two columns in Table 4 report UV luminosity $L_{220} = 4\pi D^2 F_{220,0}$, and $\mu_{e,0}$, the mean extinction corrected surface brightness within $R_e$. The remaining columns convert these to quantities involving stellar mass. To do this we employ the population models presented in the appendix which use an IMF with a Salpeter (1955) slope ($\alpha = 2.35$). We primarily calculate the mass in massive stars, $M_{\text{Ms}}$, defined to be those in the mass range $m_l = 5 M_\odot$ to $m_u = 100 M_\odot$, since our observations are not sensitive to stars with $m_\star < 5 M_\odot$. Detailed modeling of the properties of the M82 starburst indicate that its IMF may be deficient in low mass stars (Rieke et al. 1980; 1993; McLeod et al. 1993), so our conservative approach is warranted. If the actual lower limit to the IMF is $m_l = 1 M_\odot$ or $0.1 M_\odot$, then $M_{\text{Ms}}$ underestimates the total stellar mass by a factor of 2.16 or 5.52 respectively. For ionizing populations neither $L_{220}$ nor $M_{\text{Ms}}$ depend strongly on $m_u$ for $m_u > 60 M_\odot$. For example in a constant star formation rate population 10 Myr old, with a Salpeter IMF, and the above $m_u$ and $m_l$, only 11% of the mass of the IMF and 18% of $L_{220}$ comes from stars with $m_\star > 60 M_\odot$.

The conversion from $L_{220}$ to mass also depends on the star formation history of the population. The most important constraint we can place on the star formation history comes from the size of the bursts. Simultaneous star formation in an extended region is unlikely to occur over timescales shorter than the crossing time. By this we mean the time it takes for some disturbance that may effect the star formation rate to pass through the ISM. Taking the typical sizes and gas velocities observed for starbursts, the typical crossing times are on the order of 10 Myr; i.e. diameter of 500 pc, velocity dispersion of $\sim 50$ km s$^{-1}$ (MFDC, Iye et al., 1987, Marlowe et al., 1995). This provides a rough lower limit to the burst duration. It is too long to be an instantaneous starburst (ISB), so we adopt a constant star formation (CSF) rate history for the global properties of the starbursts. As noted below, the individual clusters are small enough that they can form over a much shorter timescale, and are likely to be formed in true short duration bursts.

For deriving masses we adopt $M_{\text{Ms}}/L_{220} = 0.0017 (M_\odot/L_{\text{Bol}})\odot$ which is the average mass to light ratio for CSF models with ages $1 < t \leq 100$ Myr and our adopted mass range. $M_{\text{Ms}}/L_{220}$ covers a range of a factor of 13 for the full range in star formation histories of ionizing populations. Note $M_{\text{Ms}}$ is the total initial mass in massive stars. The instantaneous mass in stars is somewhat less due to stellar winds and SNe returning mass to the ISM (see LH for detailed calculations).
The conversion from $L_{220}$ to the massive star formation rate, MSFR, has only a weak time dependence for a CSF history. We adopt

$$\text{MSFR} = \frac{L_{220}}{2.70 \times 10^{43} \text{erg s}^{-1} \text{M}_{\odot} \text{yr}^{-1}}.$$ 

The conversion factor is consistent with the above $M_{Ms}/L_{220}$ ratio for an age of 12 Myr (conveniently close to the crossing time estimated above). Similarly the effective massive star formation activity, MSFA$_e$, is the average MSFR per unit area within $R_e$:

$$\text{MSFA}_e = \frac{\text{MSFR}}{2\pi R_e^2}.$$ 

Again we stress that MSFR and MSFA$_e$ only measure the contribution of massive stars. A suitable correction factor, such as those given above, must be applied to get the total star formation rate. For comparison column 9 of Table 9 gives SFA$_e$, the star formation rate per area assuming the IMF extends down to $m_i = 0.1\, M_{\odot}$.

Figure 8 plots some of the integrated properties of the sample. Panel (a) plots MSFA$_e$ against $\log(L_{220})$, and panel (b) plots MSFA$_e$ against $\log(R_e)$. Most of our sample has $\langle \log(\text{MSFA}_e) \rangle = -0.16$ (or MSFA$_e = 0.7 M_{\odot} \text{Kpc}^{-2} \text{yr}^{-1}$) with a standard deviation of 0.16. This corresponds to $\mu_{e,0} = 15.9 \pm 0.4$ mag arcsec$^{-2}$. The exception are three outliers, I Zw18, NGC 1705 (total), and NGC 7552. The high surface brightness of NGC 1705 is due to NGC 1705-1. If it is excluded NGC 1705’s MSFA$_e$ is normal relative to the other starburst galaxies. NGC 7552 has the highest MSFA$_e$ in the sample, significantly outside (by 6$\sigma$) the range of the majority of starbursts. The high surface brightness of NGC 7552 is immediately apparent in the FOC image (despite its high $A_{220}$) and causes this image to have the highest degree of nonlinearity. However, because of the large extinction and non-linearity corrections, its quoted value for MSFA should be considered tentative. The low MSFA$_e$ of I Zw18 (5$\sigma$ lower in $\log(\text{MSFA}_e)$ than the majority of the sample) cannot be explained by mitigating circumstances. Including NGC 7552 and I Zw18 in the average does not change $\langle \log(\text{MSFA}_e) \rangle$ significantly but increases the dispersion to 0.4. Panel (c) of Fig. 8 shows a strong correlation between $\log(L_{220})$ and $\log(R_e)$. The dotted line in panel(c) shows the expected slope for constant constant surface brightness.

Panels a-c of Fig. 8 illustrate that most starbursts have roughly the same UV surface brightness and consequently that $L_{220}$ is mainly governed by the size of the star forming region. AHM find a similar result for FIRGs selected to have warm dust temperatures; specifically that $L_{IR} \propto R_e^{1.7 \pm 0.2}$ where here, $R_e$ is the H$\alpha$ half light radius. This is close to the $R_e^2$ correlation expected for constant surface brightness. The UV and IR results are important because they suggest a negative feedback mechanism is limiting the MSFA$_e$. Since we selected a starburst sample, we may be selecting galaxies with a high MSFA$_e$. Thus the mean MSFA$_e$ we find for starbursts may represent an upper limit for the larger encompassing set of star forming galaxies. In comparison normal disk galaxies have a mean H$\alpha$ surface brightness $\langle \Sigma_{\text{H}\alpha} \rangle = 3.6 \times 10^{38} \text{erg s}^{-1} \text{Kpc}^{-2}$ (Kennicutt, 1989) which corresponds to MSFA$_e = 3.8 \times 10^{-3} M_{\odot} \text{Kpc}^{-2} \text{yr}^{-1}$ (for a 10 Myr CSF model; LH and appendix). On average our starburst sample has star formation activity about 200 times more intense than normal disk galaxies, thus earning their “starburst” moniker. In addition, Lehnert (1992) finds that the range in $L_{IR}/R_e^2$ for the warm starbursts (i.e. those selected by AHM), is much smaller than for FIRGs selected with no color constraints, and that the warm FIRGs have the highest $L_{IR}/R_e^2$.

In panel (d) of Fig. 8 the extinction corrected UV and H$\alpha$ fluxes are compared. The fluxes we use are listed in Table 8. The H$\alpha$ fluxes were taken from the literature using the largest appropriate aperture. For NGC 3991 and Tol1924-416 the available H$\alpha$ data employed quite small apertures. Therefore we adopt an
$F_{220,0}$ through an aperture with matching area for this comparison. Note that the extinction correction adopted to determine $F_{\text{Ha},0}$ is that derived from the Balmer decrement, $E(B-V)_{\text{BD}}$, not $E(B-V)_{\text{UV}}$. Since both $F_{220,0}$ and $F_{\text{Ha},0}$ measure the hot star content, they are indicators of the MSFR. The Hα flux is an indicator of the ionizing stellar flux, while $F_{220,0}$ is sensitive to somewhat less massive stars, and therefore longer star formation durations. Also shown in Fig. 8d are the correlations expected from the LH models for constant star formation rate populations with ages 1, 10, and 100 Myr, and a Salpeter IMF with $m_u = 100 M_\odot$. The UV and Hα fluxes have the one to one correlation expected, but have, on average a higher $F_{220,0}$ for a given $F_{\text{Ha},0}$ than the LH models by a factor of several. There are several possible explanations for this discrepancy. The starburst galaxies may have relatively more low mass stars than the LH model either because (1) $m_U$ is lower than 100 $M_\odot$ (cf. Doyon et al. 1992), (2) the IMF slope may be steeper than a Salpeter IMF, (3) the star formation has lasted longer than 100 Myr, or (4) the MSFR is declining with time. Other explanations for the discrepancy include (5) Some of the ionizing flux is absorbed by dust grains (c.f. Panagia, 1977; Fig. 4), (6) the nebula is density bounded, or (7) the total Hα flux is not intercepted by the apertures.

5. Star clusters

Figure 9 shows histograms of the magnitudes of compact sources found using DAOFIND, during the course of the smooth-clumpy structure separation discussed in §2.2. Only sources with aperture photometry having $S/N > 5$ are shown here.

The range of $M_{220}$ shown in the histograms $\sim -9$ to $\sim -18$, shows that while some of the faintest sources in the nearest galaxies could be stars, the brightest certainly are not and must be clusters of some sort. Since an individual star cluster is expected to form over a short time ($dt < 0.1$ Myr; Larson, 1988), it can safely be assumed to be an instantaneous starburst. Assuming a Salpeter IMF slope, a lower limit to their massive star content can be found by assuming that they are at their peak UV luminosity; then $M_{M_*}/L_{220} = 5.8 \times 10^{-4} M_\odot/L_{\odot,\text{Bol}}$. The minimum $M_{M_*}$ covers a range of $6 \times 10^3 - 2.4 \times 10^5 M_\odot$, for $M_{220}$ in the range $-14$ to $-18$ mag covered by the SSCs. If the IMF extends down to 0.1$M_\odot$, then the range is from $3.3 \times 10^4 M_\odot$ to $1.3 \times 10^6 M_\odot$. This is the same mass range found in Galactic globular clusters.

5.1. Location

The clusters are preferentially found where the underlying surface brightness is highest. One indication of this phenomenon is shown in Fig. 10 which plots the fraction of total UV light arising from clumpy structure $f_{\text{clumpy}}$ as a function of MSFA$_e$. These quantities are weakly correlated, having a correlation coefficient $R = 0.45$ (we have excluded the total NGC 1705 measurement which is dominated by NGC1705-1). The correlation is in the sense that as MSFA$_e$ increases a greater fraction of the luminosity is produced in compact sources. One must be careful to not over interpret this result. $f_{\text{clumpy}}$ is the ratio of the light in compact sources to the total light. There is no $M_{220}$ cutoff to what is called a compact source, so in the nearest galaxies, especially NGC 5253, there is a significant contamination by individual stars. Also since most of the sample occupies a narrow range in MSFA$_e$ (§4.2.), the correlation is largely driven by the two outlying points, IZw18 and NGC 7552.

It is more clear that the brightest clusters are locally correlated with the highest UV surface brightnesses. This is shown in Fig. 11 which plots $M_{220}$ against the local underlying surface brightness for each galaxy, measured from the smooth component image. The distribution of points in each panel is limited at the bottom by the de-
tection limit, and on the right by the minimum $\mu_{220,0}$ of the frame. But there are no detection limits placed on the upper left of each panel, that is for bright objects on top of a weak underlying background. That this region is underpopulated in all panels can not be due to selection effects. Figure 12a shows the combined $M_{220}$ versus $\mu_{220,0}$ plot for the SSCs ($M_{220} < -14$) in NGC 1705, NGC 4670, NGC 3310, Tol 1924-416, and NGC 3991. The other galaxies were excluded because either (1) they didn’t have luminous enough clusters (IZw18, NGC 5253), or (2) they have high differential reddening and/or linearity corrections (NGC 7552, NGC 3690). Figure 12b is a histogram of the number of these clusters as a function of $\mu_{220,0}$. It is sharply peaked at a MSFA $\approx 0.9 \, M_\odot \, \text{Kpc}^{-2} \, \text{yr}^{-1}$. The width of the distribution is partially due to the slightly different limiting surface brightnesses of each frame. Panels c and d of this figure are the same as a and b except the abscissa is $\mu_{220} - \mu_{220,\text{min}}$. We see that 29%, 76%, and 93%, of the SSCs are located within 0.5, 1.0, and 1.5 mag arcsec$^{-2}$ of $\mu_{220,\text{min}}$, the peak surface brightness. In comparison 11%, 25%, and 49%, on average, of the smooth component light is located within these isophotes.

5.2. Cluster sizes

We measured the half light radius, $R_e$ of 85 compact sources. Selection for measurement was as follows. For the nearest two galaxies (NGC 5253, NGC 1705), the five brightest uncrowded objects were measured as well as the noticeably diffuse sources. Two or three point source candidates were also measured to test the limits of our technique. For the remaining galaxies, selection was by brightness. Our target was to measure all uncrowded sources with $M_{220} < -14$ (i.e. the SSCs). This was not feasible for NGC 3690 and NGC 7552 because of their high reddening correction.

Our method is to compare the objects' radial surface brightness profiles, $S_o(r)$ (in counts per pixel) to profiles of model clusters that have been convolved with the PSF. Examples of fits are shown in Fig. 13. The object profiles were extracted from the linearity corrected images$^7$ in one pixel wide circular annuli. After some experimenting we decided to discard the central annulus ($r$ ranging from 0 to 1 pixels) from the fit because of the onset of non-linearity or saturation in many of the brighter sources. The worst case of this is NGC1705-1 which is so saturated that we could not fit our UV data with this technique. Tol1924-416-1 (shown in Fig. 13) is the second worse case, it has a flat $S_o(r)$ out to $r = 2.5$ pixels, where we begin our fit. In most cases the profile was fit out to $r = 8.5 - 10.5$ pixels; the exact value depended upon crowding. In one case, NGC5253-12 (also shown in Fig. 13), the fit was extended to $r = 15.5$ pixels because of the diffuseness of the cluster. Sources with neighbors of at least comparable brightness within $r = 12$ pixels were not fitted. However, apparently elongated sources or those with faint extensions were not excluded. These may represent sources with faint companions.

The clusters were modeled by circularly symmetric Gaussian profiles. For this model $R_e = 0.5 W_{50}$. Two sets of models were made by convolving the profiles with the two empirical PSFs. A $\chi^2$ minimization technique was used to fit each $S_o(r)$ by the function

$$F(r) = a_0 + a_1 S_{m,R_e}(r),$$

where $S_{m,R_e}(r)$ represents the set of convolved model profiles, $a_0$ is the background level, and $a_1$ yields the cluster brightness. Generally the best fitting $R_e$ agreed to within 0.2 pixels for the two sets of models. Here we report the mean best fitting $R_e$. Typical external errors are $\sigma_{R_e} \approx 0.5$ pixels, and $\sigma_{m_{220}} \approx 0.2$ mag as determined from comparing the measurements of the two separate images of NGC 1705. Measurements of 65

$^7$For NGC 1705, the frames with NGC1705-1 subtracted were used.
stellar profiles in archived frames of the Galactic clusters NGC 104 and NGC 188 (taken with the same setup) were used to determine the resolution limit of our technique. We find that sources with $R_e \leq 1.52$ pixels cannot be distinguished from stars at a better than 90% confidence. The objects in NGC 5253 and NGC 1705 that were selected as likely point sources are all unresolved by our technique.

The resultant $R_e$ are shown as a function of $M_{220}$ in Fig. 14. The measurements are tabulated in Table [1], which also lists the position offsets (relative to the coordinates given in Table [3]) and magnitudes of the sources. Sources are included in this list if they had their profile fitted, or if they are bright enough, or if they are discussed earlier in the text. The brightness limit is $M_{220} < -14$ for most host galaxies, and $M_{220} < -16$ for NGC 3690 and NGC 7552 because of their large UV absorptions, $A_{220}$, due to dust extinction (Table [2]). Note that $A_{220}$, (derived in §4.1), is applied uniformly to all sources in a galaxy (i.e. assuming a uniform foreground screen). If the dust distribution is non-uniform and the sources evenly distributed, then they will preferentially be detected where the dust is thin, and $M_{220}$ may be preferentially underestimated. The apparent magnitude $m_{220}$ of the compact sources is from the aperture photometry, while $M_{220}$ is that derived from the profile fitting (where applicable).

The resolved objects have $R_e$ ranging from 0.6 to 22 pc. This is nearly identical to the range of $R_e$ found in Galactic globular clusters (van den Bergh et al. 1991). Thus the sizes of the compact sources are consistent with globular cluster sizes. However the distribution of sizes for the compact sources differs from globular clusters, with clearly a larger fraction of our sources at the high $R_e$ end; 14% of our sample have $R_e > 10$ pc, while only 3% of the Galactic globular clusters are this large. In addition the resolved sources appear to follow a $R_e \propto L^{1/2}$ correlation (i.e. constant surface brightness), which is not seen in the Galactic globular cluster sample.

There are a number of reasons why we should be wary of these results. (1) 42% of the sample have only upper limits in $R_e$. (2) There is no correlation of $R_e$ with $L$ within a galaxy (in NGC 3991 the quantities are anti-correlated). (3) There is a strong Malmquist bias in our sample: for galaxies at large distances ($D$) we can not see the faintest clusters, and at small $D$ there are very few of the highly luminous SSCs. The exception is NGC1705-1 which is saturated in our images. (4) Many of the sources at large $D$ appear elongated, and thus may have faint neighbors. (5) The size of the fitted region increases with $D$. Since clusters are preferentially found embedded in the highest surface brightness background the chance of contamination increases as $D^2$ especially if the $\mu$ profile is peaked towards the cluster (e.g. NGC 1705, NGC3690-Aa,Ab; see fig 5).

To help compensate for the Malmquist bias, we supplemented our sample with measurements of NGC1705-1 and the two SSCs in NGC 1569 ($D = 2.2$ Mpc) using the planetary camera (PC) images presented by (O’Connell et al. 1994). Profiles from their summed F555W and F785LP images were measured with a technique nearly identical to that used on the FOC data. The only difference was that the smallest annulus was not discarded. We find $R_e = 1.1 \pm 0.3, 1.7 \pm 0.2, \text{ and } 1.2 \pm 0.2$ pc for NGC1705-1, NGC1569-1, and NGC1569-2 respectively. These are the mean $R_e$ in the two bands, with the error representing half the difference between the bands. The sizes for these nearby SSCs are shown in Fig. 14.

To test the effects of contamination we simulated images of NGC 1705 at $D$ ranging from 6.2 to 49 Mpc. The intrinsic image was taken to be the Lucy deconvolved frame of NGC 1705b, which had NGC1705-1 removed prior to deconvolution. NGC1705-1, was then added back to this image as a circularly symmetric Gaussian profile with $R_e = 1.1$ pc as measured in the PC images.
The intrinsic image was rebinned to simulate the intrinsic image at different $D$, and then deconvolved with the PSF. The cluster profiles from the resulting images were then measured. We find that at its observed luminosity NGC1705-1, would remain unresolved out to 49 Mpc. However, we would measure $R_e = 6.9$ pc for a cluster half as bright on top of the same background at a distance of 37 Mpc. Thus, the amount of contamination from the background depends critically on the contrast of the cluster against the background.

We conclude that the size estimates of the more distant clusters should be treated with caution. Although some of these objects may indeed be isolated clusters with $R_e \approx 10$ pc, the data are not sampled well enough to measure smaller sizes, and $R_e$ could easily be contaminated with high surface brightness structure correlated with the clusters. To be safe one should not try to measure $W_{50} = 2R_e$ smaller than the Nyquist width. So to unambiguously measure clusters with $R_e = 1$ pc with the HST one should not look at galaxies beyond $D = 9$ Mpc.

NGC 1569, NGC 5253, and NGC 1705 meet this criterion. The resolved sources in these galaxies have $R_e \leq 2.9$ pc, and show no correlation of $R_e$ with $L$. The median of the clusters in this sub-sample is 1.3 pc, smaller than the Galactic globular cluster sample of van den Bergh et al. (1991) which has a median $R_e = 2.6$ pc. This may not represent a real difference since the model surface brightness profiles of van den Bergh et al. (1991) have more power at large radii than a Gaussian. Recently O’Connell et al. (1995) have measured the sizes of SSCs in M82 ($D = 3.6$ Mpc) and find a mean $W_{50} \approx 3.5$ pc from deconvolved HST images. This translates to $R_e \approx 1.8$ pc if a Gaussian profile is assumed for the clusters. Therefore the accumulated evidence on nearby starbursts is that the $R_e$ of SSCs is similar to that of typical globular clusters.

Whitmore et al. (1993) and WS measured cluster $R_e$ in the merging systems NGC 7252 and NGC 4038/4039 using WFPC-1 data. They also adopt a Gaussian model for the cluster profiles, but derive $R_e$ from only one data point for each object: the magnitude difference between the light measured in apertures of $r = 0.5$ and 3 pixels. They measure typical $R_e \approx 7 - 20$ pc for the clusters in these systems, assuming revised distances of $D = 65, 19$ Mpc respectively ($H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$). These sizes are at the large end of the size distribution of Galactic globular clusters as pointed out by van den Bergh (1995). However NGC 7252 and NGC 4038/4039 are too distant to reliably measure $R_e$ as small as a few pc and the caveats concerning our measurements at large $D$ also apply. In particular the area they fit (out to $r = 27 - 40$ pc) may be contaminated by surrounding high surface brightness structure.

5.3. Luminosity Function.

Figure 15 shows the combined $M_{220}$ luminosity function (LF) of SSCs excluding those in NGC 7552 and NGC 3690 (because of their large extinction corrections and corresponding bright limiting magnitude). The $M_{220}$ magnitudes produced by the profile fitting are somewhat brighter than than those from the aperture photometry because most SSCs are resolved. To avoid biasing the LF, the sources with just aperture photometry have $M_{220}$ in Table 10 corrected by the median in $M_{220}$ (fit) $- M_{220}$ (ap. phot) = -0.26 (range is from -1.7 to 0.4 mag) before constructing the LF.

The luminosity function is rising out to the faint magnitude limit of $\sim -14$ with no sign of decrease. Because of the low total number of sources in the LF, and the differing distances and limiting magnitudes of the sample we do not fit the LF. Instead we compare it to a power law LF: $\phi(L)dL \propto L^\alpha dL$, where $\phi(L)dL$ are the number of clusters with luminosities between $L$ and $L+dL$, and $\alpha = -2$. This slope is chosen because
it is representative of the $\alpha$ of several other systems of young clusters. For example Elson & Fall (1985) find $\alpha = -1.5$ for LMC clusters. The LF they present for Galactic open clusters was not fit but appears to be a power law with a steeper slope. WS find the SSC LF in the merging system NGC 4038/4039 are also well fit by a power law LF with $\alpha = -1.78 \pm 0.05$. Kennicutt et al. (1989) find that the H$\alpha$ LFs of H II regions in spiral galaxies are well fit by a power law with $\alpha = -2.0$. This is also presumably the LF slope of the ionizing clusters within each H II region. Thus systems of young clusters, including SSCs, appear to be well represented by a power law LF with $\alpha \approx -2$.

5.4. The nature of SSCs

There is much speculation in the literature as to whether SSCs represent proto-globular clusters (e.g. MFDC; Whitmore et al. 1993; WS), or are merely high luminosity open clusters (e.g. van den Bergh, 1995). We do not wish to enter a semantics debate on the distinctions between open and globular clusters (c.f. Stetson, 1993). A better way to express the question is would SSCs resemble globular clusters if left to evolve? This is especially relevant to elliptical galaxies. The hypothesis that these are formed by mergers of disk galaxies (Toomre, 1977) which result in the creation of SSCs may explain the high specific frequency of globular clusters around E galaxies (Ashman & Zepf 1992). To answer this question it is important to determine whether the ensemble properties of SSCs are consistent with globular clusters.

Our results indicate that the range in luminosity is consistent with that expected for young globular clusters if they had an IMF extending up to $m_u \approx 100 \, M_\odot$. Similarly the range in $R_e$ is consistent with the present range seen in globular clusters. However the difficulties come when trying to compare the detailed distribution of $R_e$ and $L$. As discussed above, when only the nearest SSCs are considered, the $R_e$ of globular clusters and SSCs are consistent. The projected effective mass density of NGC1705-1 (the densest cluster for which we have a reliable size) is $\Sigma \gtrsim 5 \times 10^4 \, M_\odot \, pc^{-2}$ if its stellar IMF extends down to $m_i = 0.1 \, M_\odot$. This limit (corresponding to the peak $L_{220}$ of an SSC) is similar to the projected central density of M80 and 47 Tuc $\Sigma \approx 7 \times 10^4 \, M_\odot \, pc^{-2}$ (Peterson & King, 1975).

The available LF of SSCs are well characterized by power laws with slope $\alpha \approx -2$, and are not consistent with that of present day globular clusters. The latter have an approximately Gaussian luminosity function in the $N$ versus $M_V$ plane (Harris, 1991). The globular cluster luminosity function is essentially a mass function, since the age spread amongst globular clusters is small compared to their mean age. This is not the case for SSCs which are still being formed in their host starbursts. Meurer (1995b) shows how the power law SSC LF in the Antennae system is well modeled by a globular cluster mass function and continuous cluster formation. This, of course, does not mean that a Gaussian mass function is the only mass function that can reproduce the power law LF of SSCs. Even if the SSC mass function starts as a pure untruncated power law, it is conceivable that a lower mass truncation could be imposed by destruction mechanisms (Fall & Rees, 1977; see however, Fall & Rees, 1988). Then the SSC LF may evolve into a Gaussian if the SSCs are placed in the right environment. All in all, the LF alone does not provide a convincing constraint on the nature of SSCs.

At this stage, the known properties (mainly size and luminosity) of SSCs are consistent with the hypothesis that they represent proto-globular clusters. There are other properties that can be measured to further test this hypothesis. Spectroscopy, colors and extinction measurements would be useful in determining the ages for SSCs. From these it might be possible to construct a true mass function for the SSCs. One prob-
lem with the proto-globular cluster hypothesis is that we don’t even know if the stellar mass functions of globular clusters and SSCs overlap; our SSC observations are only sensitive to stars with $m_\ast > 5 M_\odot$, while the only stars presently in globular clusters have $m_\ast < 1 M_\odot$. Since most of the mass in the IMF should come from the low mass stars, mass estimates of SSCs will be crucial in determining if they could evolve into globular clusters. The measurements will be difficult since globular clusters typically have velocity dispersions $\sigma \lesssim 10 \text{ km s}^{-1}$ (Peterson & King, 1975). Finally, it would also be good to have measurements of the metallicities of SSCs to see if they agree with globular clusters.

6. Summary: the anatomy of starbursts

High resolution ultraviolet images, combined with HST and IUE spectroscopy have allowed us to dissect the structure of starburst galaxies covering a large range of luminosities and morphologies. Despite their differences we can now begin to describe the anatomy of a starburst.

Dust distribution. A significant component of the dust content of starburst galaxies must be in a foreground screen near the starburst. This is deduced from the observed strong correlation of the infrared to UV flux ratio $\log(F_{\text{FIR}}/F_{220})$ with the UV spectral slope, $\beta$, for our sample and other galaxies detected with both the IUE and IRAS satellites. This correlation shows that as the spectral energy is redistributed from the UV to the far infrared, the spectrum is reddened. The range in $\beta$ over which the correlation applies rules out geometries where the dust is mixed evenly with the UV emitting stars or in a very clumped distribution. Only the foreground screen geometry adequately models this range. The average ratio of $60\mu m$ and $100\mu m$ flux suggests that the screen is located $\sim 2.5R_e$ from the starburst center.

It is also clear that not all the dust is in a uniform foreground screen. Our UV images clearly show dust lanes in some cases (NGC 5253, NGC 3310, NGC 7552). Data from other wave bands indicate that the extinction distributions in the most highly reddened galaxies, NGC 3690 and NGC 7552 are not uniform. Nevertheless, even in these cases the observed reddened values of $\beta$ indicate that foreground dust has a large covering factor and may be responsible for a large fraction of the far-IR flux.

Overall morphology. The UV morphology of a starburst is highly irregular, composed of one or several diffuse, usually oddly shaped, cloud(s) with embedded compact sources. The size and luminosity of the brightest compact sources indicate that they are star clusters. The three nearest galaxies in our sample (NGC 5253, NGC 1705, IZw18) are near enough to resolve into stars which are spread throughout the diffuse component, suggesting that most of the diffuse light is unresolved stars and not scattered light. The radial profiles are not well parameterized by either an exponential or an $r^{-0.25}$ law.

The size of the clouds allow the star formation duration to be constrained: it is unlikely that simultaneous star formation is occurring over extended regions on a timescale shorter than the crossing time. This is typically $\sim 10$ Myr for typical gas velocities observed in starbursts. The timing arguments are less stringent for the clusters each of which are expected to form over timescales $\Delta t < 0.1$ Myr (Larson, 1988). The star formation history is then likely to be more or less continuous over timescales of $\gtrsim 10$ Myr for the diffuse component, with the clusters representing true staccato “instantaneous” starbursts.

Most starbursts (7/9 galaxies) are observed with a preferred effective surface brightness, $\langle \mu_{e,0} \rangle = 15.9 \pm 0.4$. The corresponding effective star formation rate per area in high mass stars ($5 - 100$ $M_\odot$) is $MSF_{e} \approx 0.7 M_\odot \text{Kpc}^{-2} \text{yr}^{-1}$ for a Salpeter (1955) IMF slope (or $SFA_{e} = 3.5 M_\odot \text{yr}^{-1} \text{Kpc}^{-2}$ if the IMF extends down to $0.1 M_\odot$). Since we have selected by UV brightness we may
be preferentially selecting galaxies with a high MSFA$_e$, at least compared to “normal” galaxies. Thus $\langle \mu_{e,0} \rangle$ may represent the upper limit to the UV intensity that one can find in a galaxy. Similar results are found in the far IR by Armus et al. (1990) and Lehnert (1992). These results suggest that there is a negative feedback mechanism limiting the MSFA$_e$ and thus the UV radiation field. What this mechanism is, is not apparent from our observations, but there are numerous possibilities including mechanical heating from SNe and winds, cosmic ray heating and the intense UV radiation field itself.

Cluster Formation. UV bright star clusters are found within all starbursts, and very few are found outside of them. Young luminous clusters are increasingly being found with the HST; examples are noted in §I. The host galaxies all have starburst characteristics. Thus cluster formation is an important mode of star formation in starbursts. Clusters are manufactured at a high efficiency. On average $\sim 20\%$ of the UV light comes from clusters.

The fraction of light in clusters is (weakly) correlated with $\mu_{e,0}$; galaxies with the most intense UV field have more light in clusters. As one increases the UV field strength, more of the star formation is in clusters. This is also seen locally; 90% of the brightest clusters, the “super star clusters” or SSCs, are found to have an underlying $\mu_{220}$ within 1.5 mag arcsec$^{-2}$ of the most intense found in the starburst.

Thus SSCs are formed in the heart of a starburst. This suggests that cluster formation is related to the mechanism that regulates $\mu_{e,0}$ of the whole starburst. The observations summarized by Larson (1993) indicate that cluster formation is triggered by neighboring star formation. Perhaps clusters may inhibit further star formation, at least in the immediate surroundings. Indeed the effect of cluster formation on the ISM can be much more dramatic than a 20% contribution to $L_{220}$. For example Malumuth & Heap (1994) shows that a simple census of the ionizing stars in the cluster NGC 2070 in the 30 Doradus nebula alone can account for 40% of the ionizing flux of the whole nebula which is $\sim 1$ Kpc across. Another example is NGC1705-1, which is probably the dominant energy source of NGC 1705’s spectacular galactic wind which extends out to the Holmberg radius (Meurer et al. 1992; Meurer 1989).

The nature of SSCs. The ranges in both half light radius $R_e$ and UV luminosity $L_{220}$ of SSCs are consistent with those expected for young “proto-”globular clusters. The median $R_e$ of SSCs with $D < 9$ Mpc is consistent with the $R_e$ of present day globular clusters. We have shown that the $R_e$ measurements of more distant SSCs (e.g. ours and those of Whitmore et al. 1993; Whitmore & Schweizer 1995) are likely to be contaminated by the high surface brightness structure correlated with the presence of SSCs. The SSC luminosity function (LF) is well characterized by a power law with slope $\alpha \approx -2$ (this work and Whitmore & Schweizer, 1995) which is similar to the LFs of Galactic open clusters and LMC clusters (Elson & Fall 1985) and HII regions (Kennicutt et al., 1989) but not that of Galactic globular clusters (Harris, 1991). Because SSCs are not coeval whereas Galactic globular clusters are (in effect), the SSC LF may be consistent with a globular cluster mass function (Meurer, 1995b).

Thus SSCs remain plausible proto-globular cluster candidates. Mass and metallicity estimates of SSCs could confirm whether SSCs are indeed proto-globular clusters. If so, then the globular cluster forming clouds in the Searle & Zinn (1978) model of galaxy formation may have looked like starbursts. It is interesting that on purely theoretical grounds Larson (1988) came to the same conclusion.

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A. Ultraviolet properties of young stellar populations

A.1. Models

In order to translate raw measurements of UV properties of starbursts into physical quantities such as mass, reddening, and star formation rate, we have measured modeled spectra of stellar populations. We primarily employ spectra generated from the code of Leitherer and Heckman (1995; hereafter LH) with ages from 1 to 100 Myr. A power law IMF with a Salpeter (1955) slope of $\alpha = 2.35$ (eq. 2 of LH) with mass limits $m_l = 1.0 M_\odot$ to $m_u = 100 M_\odot$ was adopted. We refer to these parameters as the “standard” IMF. Two star formation histories were considered: an instantaneous star burst (ISB) and a constant star formation rate (CSF). All models employ solar metallicity evolutionary tracks and stellar atmospheres. The broad band properties examined here are not significantly affected by metallicity. The LH models calculate both the stellar and nebular continuum contributions to the total flux. We consider the stellar and total (= stellar + nebular continuum) spectrum separately.

We supplemented the LH models with models from the Bruzual & Charlot (1993) Galaxy Isochrone Synthesis Spectral Evolutionary Library (GISSEL). The GISSEL models also have a solar metallicity and a Salpeter IMF, but with mass limits $m_l = 0.1 M_\odot$ to $m_u = 125 M_\odot$.

The ISB models have been normalized to an initial mass of $10^6 M_\odot$ formed over the standard IMF. The CSF models are normalized to a star formation rate of $1 M_\odot$ yr$^{-1}$ over the same mass range. Note that in both cases the GISSEL models still include the flux of the stars outside the LH mass range, although the extra UV flux is negligible.

A.2. Measurements

Broad band magnitudes, $m_\lambda$, were extracted with the SYNPHOT package in IRAF using the STMAG form:

$$m_\lambda = -2.5 \log \left( \frac{\int f_\lambda(\lambda) T(\lambda) \lambda d\lambda}{\int T(\lambda) \lambda d\lambda} \right) - 21.1,$$

where $f_\lambda(\lambda)$ is the flux density in erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$, and $T(\lambda)$ is the dimensionless passband throughput, in this case defined by the combined throughput of the HST optics (pre-COSTAR), the FOC F/96 camera, and the F220W filter. This $T(\lambda)$ has a pivot wavelength $\lambda_c = 2320$ Å and FWHM = $W_{50} = 580$ Å. The mean flux density is then

$$\langle f_{220} \rangle = 10^{-0.4(m_{220}+21.1)} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}.$$ 

We define $F_{220}$ and $L_{220}$ to be

$$F_{220} = \lambda_c \langle f_{220} \rangle$$
\[ L_{220} = 4\pi D^2 F_{220}. \]

A source with a 220 luminosity equal to the sun’s Bolometric luminosity, that is with \( L_{220} = L_{\odot, \text{Bol}} = 3.83 \times 10^{33} \text{ erg s}^{-1} \) (Allen, 1973) will have an absolute magnitude in this system of \( M_{220} = 3.55 \).

Figure 16 shows the temporal evolution of various quantities of interest. Panels on the left are for ISB populations, those on the right are for CSF populations. It is immediately apparent that the LH and GISSEL are in good agreement. The rapid fluctuations in the LH ISB models in some panels are an artifact of insufficient mass resolution in the models generated here. \( M_{220} \) is the absolute magnitude. \( \beta \) is the UV spectral slope and is extracted by fitting the spectra with \( \log(f_\lambda) = C + \beta \log(\lambda) \) using the points in the ten spectral windows defined by Calzetti et al. (1994; hereafter C94). The relatively low spectral resolution LH and GISSEL models were first interpolated to a 2˚ pixel size, to make sure there were sufficient data points in each window. The color 220 – \( V \) (= \( m_{220} - m_V \)) is presented as a tie in to other colors which are calculated by LH and Bruzual and Charlot (1993). The redleak parameter, \( RL \), is defined as \( RL = m_{220}(\text{square}) - m_{220} \), where \( m_{220}(\text{square}) \) is \( m_\lambda \) for a square \( T(\lambda) \) having a central wavelength \( \lambda_c = 2320 \text{ Å} \), and width \( \Delta \lambda = 580 \text{ Å} \). The parameter, \( NC = m_{220}(\text{stars}) - m_{220}(\text{total}) \), represents the amount of contamination of the total light by nebular continuum. The evolution of \( \log(L_{220}/L_T) \), where \( L_T \) is the total luminosity, was also calculated but not shown in this figure (the evolution is similar to that of 220 – \( V \)).

Figure 16 also shows the mass to light ratio, \( M/L_{220} \). The numerator represents the total initial mass of the stars. This is not the same as the instantaneous mass in stars since a large fraction of the initial mass is returned to the ISM via stellar winds and SNe. LH provide detailed calculations of the rate of mass return to the ISM.

The \( M/L_{220} \) results are for the standard IMF which extends down to 1 \( M_\odot \). So what mass stars are F220W measurements most sensitive to? This was estimated by using the LH code to construct CSF models at \( t = 10 \) Myr (a typical ionizing population), in which \( m_u \) varies between 3 and 120 \( M_\odot \), while the number of stars with \( m_u < 3M_\odot \) is held constant. Figure 17 shows the change in \( m_{220} \) (stellar component only) as a function of \( m_u \), relative to the standard IMF. Thus for the standard IMF, 50% of the F220W light is produced by stars with \( m_u < 28M_\odot \), and only 5% by the stars with \( m_u < 8M_\odot \). If \( m_u = 30M_\odot \) then the 50% and 5% levels are reached for \( m_u < 18,6M_\odot \) respectively. So for the standard IMF slope and 30 \( \leq m_u/M_\odot \leq 100 \), the typical emitting star has \( m_u \approx 20M_\odot \), and stars with \( m_u < 5M_\odot \) produce negligible emission.

With the standard IMF, the luminosity is mostly produced by the high mass stars while the mass is heavily weighted towards the low mass stars. Therefore, the mass to light ratio is highly dependent on \( m_u \). If \( m_u = 5M_\odot \) or 0.1 \( M_\odot \), then the \( M/L_{220} \) in Fig. 16 should be multiplied by 0.46 or 2.55 respectively.

Figure 16 shows that NC drops to zero by \( t = 10 \) Myr for the ISB models. This indicates that by this age there is no ionizing flux for ISB models. Since starbursts display a recombination spectrum, they must have \( t < 10 \) Myr if they were formed in a true instantaneous burst. If the CSF model is appropriate they can have any age, although in this paper we will only consider \( t < 100 \) Myr. Figure 16 shows that \( \beta < -2.2 \) and \( RL \) is insignificant for ionizing populations. It is also clear that RL is insignificant for unreddened ionizing stellar populations. In Table 1 we present time averages, and ranges for \( 220 - V, RL, NC, \beta, \log(L_{220}/L_T) \), and \( M/L_{220} \) (with three different \( m_u \)), for ionizing populations. These results are for the total flux (stellar plus nebular continuum) models of LH. The averages are for equally spaced points in \( \log(t) \) over the range \( 6 \leq \log(t/(1yr)) \leq 7 \) for the ISB mod-
els and $6 \leq \log(t/(1\text{yr})) \leq 8$ for the CSF models.

### A.3. Reddening and extinction

We examined how $m_{220}$ and $\beta$ are affected by four extinction laws: (1) the Galactic law of Seaton et al. (1979); (2) the LMC law of Howarth (1983); (3) the starburst law of Kinney et al. (1994; K94); and (4) the starburst law of C94. We explore their effects on CSF models with ages 1, 10, and 100 Myr. Tests show that our results also hold for ISB models with $t < 10$ Myr.

We define UV “color excess” to be

$$E(\beta) = \beta - \beta_0,$$

where $\beta_0$ is the unreddened UV slope. The relationship between $E(\beta)$ and $E(B-V)$ is extremely well fit by a linear relationship:

$$E(\beta) = r_\beta E(B-V).$$

The values of $r_\beta$ for the four reddening laws are given in the second column of Table 12. The residuals of the fits $(E(\beta) - r_\beta E(B-V))$ have an rms $\leq 0.0001$ in all cases. That the UV and optical color excesses should be related by a single slope makes sense, since the strongest terms in the reddening laws are essentially power laws. However, the Galactic and LMC extinction law have a significant bump at $\lambda = 2175$ Å which is thought to be due to small grains perhaps with graphite cores (Mathis, 1994). The continuum regions used to define $\beta$ avoids the peak of this bump, but not its wings. The values of $r_\beta$ are decreased due to the wings of the bump for the LMC and (especially) Galactic laws. Therefore, for these laws, the value of $r_\beta$ depends critically on which continuum regions are adopted. The values quoted here are only for the continuum regions of C94.

We parameterize the effects of extinction on the UV fluxes in terms of the ratio of total to selective extinction $X_\lambda$:

$$X_{220} = \frac{A_{220}}{E(B-V)}$$

where $A_{220} = m_{220} - m_{220,0}$ is the extinction and $m_{220,0}$ is the intrinsic magnitude. This ratio is shown as a function of $E(B-V)$ for the three representative CSF models, and the four extinction laws in Fig. 18. $X_{220}$ declines with $E(B-V)$ because of the broad passband; as $E(B-V)$ increases the effective wavelength shifts to the red where $X_\lambda$ is lower.

For each reddening law, simple polynomial fits to $X_{220}(E(B-V))$ were made:

$$X_{220} = \sum_{i=1}^{n} a_i E(B-V)^i,$$

The highest order used was $n = 2$ or 3. The polynomial coefficients $a_i$ and the rms of the fits are reported in Table 12.

The four extinction laws are very similar in the optical but diverge markedly in the UV. It is better to parameterize the UV extinction curves in terms of the local (UV) color excess. The bottom panel of Fig. 18 shows $X'_{220} = \frac{A_{220}}{E(\beta)} = X_{220}/r_\beta$, as a function of $E(\beta)$. To simplify the diagram, we show only the fits to $X_{220}$ after transforming coordinates from $E(B-V)$ to $E(\beta)$. The $X'_{220}$ curves have a much simpler behavior than the $X_{220}$ curves.

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This 2-column preprint was prepared with the AAS \LaTeX\ macros v3.0.
Fig. 1 – Grey scale representation of the reduced FOC images. Panels are as follows: (a) NGC 1705 frame a; (b) I Zw18; (c) NGC 3310; (d) NGC 3690; (e) NGC 3991; (f) NGC 4670, (g) NGC 5253; (h) Tol1924-416; (i) NGC 7552. The images are reproduced with a square root stretch with the exception of the NGC 7552 image which uses a cube root stretch. In all panels the long and short arrows point north and east, respectively, and have lengths of 2″ and 1″.

Fig. 2 – FOC $m_{220}$ measurements compared to those from IUE. The dotted line marks where they are equal.

Fig. 3 – Central region of NGC 1705. Top: NGC 1705a frame before subtracting model of NGC1705-1; bottom: after subtraction of NGC1705-1. The arrows indicate the orientation and scale. The long arrow is 1″ long and points to the north, the shorter 0.5″ long arrow points to the east.

Fig. 4 – Schematic representation of the contents of each frame, after rotating so north is up and east is to the left. The $\Delta \alpha$, $\Delta \delta$ coordinates are the offsets to the east and north respectively from the coordinates listed in Table 3. The FOC frame is shown as the large tilted square, while the shaded areas are the regions masked out of the image when determining the surface brightness profile. The contours indicate isophotes in the smooth component images. They are drawn from the sequence 0.25%, 0.5%, 1.0%, 2.5%, 5%, 10%, 25%, 50%, 75%, 90% of the peak surface brightness in the smooth component image. The compact sources are marked by overplotted solid circles and crosses. The size of the circle decreases linearly with $m_{220}$, while the cross size remains fixed. The correspondence between $m_{220}$ and symbol is given in panel a. The galaxies, the faintest isophote shown (in mag arcsec$^{-2}$), and the corresponding percentage of the peak are: (a) NGC 1705a, 20.08, 1%; (b) NGC 1705b, 20.05, 1%; (c) I Zw18, 21.95, 1%; (d) NGC 3310, 18.52, 10%; (e) NGC 3690, 20.80, 2.5%; (f) NGC 3991, 21.27, 1%; (g) NGC 4670, 20.64, 1%; (h) NGC 5253, 19.33, 5%; (i) Tol1924-416, 21.38, 1%; and (j) NGC 7552, 21.42, 0.25%. **** NOTE CONTOURS NOT SHOWN IN FTP FILE fig04.ps! ****

Fig. 5 – Surface brightness profiles extracted from the images. The thick lines are profiles derived from the total image, while the thin lines connecting the dots shows the profiles derived from the smooth component images. The dotted lines show the effect of changing the “sky” level by $\pm 1\sigma_{\text{sky}}$ on the smooth component profile.

Fig. 6 – The far infrared excess $\text{IRX} \equiv \log(F_{\text{FIR}}/F_{220})$ plotted against UV spectral slope, $\beta$. The $F_{220}$, and $\beta$ have been corrected for Galactic foreground extinction using the Seaton (1979) extinction law (see appendix). Galaxies in our sample are indicated by solid circles. Fluxes are tabulated in Table 8. The downward pointing arrow marks the upper limit of IRX for I Zw18 which was undetected by IRAS. Additional galaxies from K93 detected by both IRAS and IUE are indicated by crosses. The range $\beta_0 = \pm 2.5$ for unreddened ionizing populations (see appendix) is shown as the hatched region. The curves show the relationship for the near foreground screen models discussed in the text and four extinction laws: Galactic (solid line), LMC (dotted), and the starburst extinction laws of C94 (dashed), and K94 (dot dash).

Fig. 7 – $\beta$ plotted against Balmer decrement determined reddening, $E(B-V)_{\text{BD}}$. The effects of reddening a $\beta_0 = -2.5$ spectrum using the extinction laws of K94 (assuming that $E(B-V)_{\text{UV}} = E(B-V)_{\text{BD}}$) is shown with the dot-dashed line (appendix).

Fig. 8 – Global properties of the sample. Panel (a) plots the effective surface brightness in terms of the effective massive star formation rate per unit area, $\text{MSFA}_e$ (see text for definition), against UV luminosity, $L_{220}$. Panel (b) plots $\text{MSFA}_e$ against the effective radius of the starburst, $R_e$. Panel (c) plots $L_{220}$ against $R_e$. Panel (d) plots...
the extinction corrected UV flux \( F_{220,0} \) against the corresponding H\( \alpha \) flux, \( F_{\text{H} \alpha,0} \). The units are MSFA\( _e \): \( M_\odot \) Kpc\(^{-2}\) yr\(^{-1}\), \( L_{220} \): erg s\(^{-1}\), \( R_e \): pc, and \( F_{\text{H} \alpha,0} \). \( F_{220,0} \): erg cm\(^{-2}\) s\(^{-1}\). Data points are represented with filled circles except for: (1) NGC 3690, shown as squares, all three components are shown in panels (a–c), while the integrated fluxes are shown in panel (d); and (2) NGC 1705, the solid pentagon includes the light of NGC1705-1, the open pentagon excludes it. The two symbols for the NGC 1705 are connected by a solid line. The dotted line in panel (c) shows a line of constant surface brightness. The dotted, dashed, and dot-dashed lines in panel (d) are the expected correlations for constant star formation rate populations of ages 1, 10, and 100 Myr respectively from the models of LH, assuming a Salpeter IMF over the mass range 1 – 100 \( M_\odot \). Note that in panel (d) the UV fluxes are dereddened by \( E(B-V)_{\text{UV}} \), while the H\( \alpha \) fluxes are dereddened by \( E(B-V)_{\text{BD}} \). Tables 2, 8, and 9 contain the quantities used to construct this figure.

Fig. 9 – Histograms of compact source absolute magnitudes, \( M_{220} \). The bottom scale on each panel shows the absolute magnitude where the full extinction correction, \( A_{220,T} \), has been applied, while the top scale shows the scale where only the Galactic extinction \( A_{220,\text{gal}} \) has been removed (\( A_{220} \) values are given in Table 2). Note, this is the only figure that shows \( M_{220} \) with just the \( A_{220,\text{gal}} \) correction. All remaining figures show \( M_{220} \) of the sources with the full extinction correction. For the NGC 1705 histogram, objects detected in both frames are given a weight of 1, and those detected in only one frame have a weight of 0.5.

Fig. 10 – Fraction of UV light in the clumpy image, \( f_{\text{clumpy}} \) plotted against MSFA\( _e \). Symbols are the same as in fig. 8.

Fig. 11 – Absolute magnitude, \( M_{220} \), versus local underlying surface brightness, \( \mu_{220,0} \), for all compact objects. \( \mu_{220,0} \) was extracted from the average surface brightness in the smooth component image within a 0.34′′ × 0.34′′ box centered on each object. \( M_{220} \) is from radial profiles fits for those objects marked with an open square, and are from the aperture photometry for all other sources. Objects identified in only one of the NGC 1705 frames are marked with a cross. The top axis converts \( \mu_{220,0} \) to the corresponding massive star formation rate per unit area, MSFA.

Fig. 12 – Panel a shows \( M_{220} \) versus \( \mu_{220,0} \) for the SSCs in the lightly reddened starbursts NGC 1705 (closed pentagon), NGC 3310 (closed circles), NGC 3991 (open stars), NGC 4670 (closed triangles), and Tol1924-416 (open squares). The upper scale on panel a converts \( \mu_{220,0} \) to the massive star formation rate per unit area, MSFA. Panel b shows the histogram of number of these clusters as a function of \( \mu_{220,0} \). Panels c and d are the same as a and b except \( \mu_{220,0} - \mu_{220,\text{min}} \) is plotted as the abscissa.

Fig. 13 – Examples of compact source radial profile fits. Those on the left side are resolved, those on the right are essentially unresolved (\( R_e \leq 1.52 \) pixels). \( S(r) \) is the mean count level in circular annuli. The errorbars are equal to \( \sigma/n^{1/2} \), where \( \sigma \) is the standard deviation about the annular mean, and \( n \) is the number of pixels in the annuli. The solid line is the best fitting model, and the dotted line is the best fitting unbrodened PSF. The points marked with small symbols were not used in the fits. These particular sources are illustrated because: NGC5253-12 is the most diffuse source measured (in angular terms); NGC5253-43 illustrates a source selected by eye as a probable point source; NGC1705-4 was selected by eye for its apparent resolution; Tol1924-416-1 suffers the most central non-linearity/saturation other than NGC1705-1; NGC4670-7 is a typical barely resolved cluster; and NGC3690-1 is a typical unresolved SSC.

Fig. 14 – The main panel plots the effected radius, \( R_e \), of cluster candidates against absolute magnitude, \( M_{220} \). The vertical line shows the
confusion limit with individual stars. The dotted line has a constant surface brightness ($\mu_{220,0} = 9.57$ mag arcsec$^{-2}$) 625 times more intense than the average integrated $\mu_{e,0}$ of starbursts. Typical external error bars are shown in the upper left. The correspondence between symbols is shown in the lower panel. The data points for the SSCs in NGC 1569 and NGC1705-1 were measured from planetary camera data as discussed in the text. The $M_{220}$ of the NGC 1569 clusters were derived from their $M_{555}$ (O’Connell et al., 1994) assuming they have the same $M_{220} - M_{555}$ as NGC1705-1. The right panel shows the histogram of $R_e$ of Galactic globular clusters from van den Bergh et al. (1991).

Fig. 15 – Luminosity function of the lightly reddened SSCs. The smooth dotted line is a luminosity function of the form $\phi(L) \propto L^{-2}$. The normalization is to the total number (59) of objects with $-15 \geq M_{220} > -18$.

Fig. 16 – Evolution of various properties in the F220W passband. The panels on the left are for ISB models, those on the right are for CSF models. In all panels solid lines represent the stellar component of the LH models, the dotted lines represent the total light (stellar plus nebular) from the LH models, and the dashed lines the GISSEL models (in which only the stellar component is modeled). The dash dot dash line at $M_{220} = -10.7$ indicates the peak absolute magnitude of a star having $m_* = 100 M_\odot$.

Fig. 17 – Effect of changing $m_u$ while keeping the mass normalization constant. The curve shows the difference in absolute magnitude, $M_{220}$, between two CSF models at an age of 10 Myr. Both have a Salpeter (1955) and the same mass in stars in the range $1 \leq m_*/M_\odot \leq 3$. One has a fixed IMF upper limit of $m_u = 100 M_\odot$ while in the other $m_u$ varies between 3 and 120 $M_\odot$.

Fig. 18 – The ratio of total to selective extinction $X_{220}$ as a function of $E(B - V)$ in the top panel and $E(\beta)$ in the bottom panel. The top panel shows $X_{220}$ for the four reddening laws and the three CSF models of LH, as well as the polynomial fit to $X_{220}$ for each law. In the bottom panel only the transformed fits are shown.
Table 1
Properties of the sample galaxies

| Galaxy       | $V_r$  | $D$   | $M_B$ | Morphology               |
|--------------|--------|-------|-------|--------------------------|
| NGC 1705     | 629    | 6.2   | −16.4 | Amorphous/BCD            |
| I Zw18       | 756    | 14.3  | −14.7 | BCD                      |
| NGC 3310     | 980    | 17.9  | −20.1 | SAB(r)bc pec             |
| NGC 3690     | 2992   | 44.   | −21.3 | SBm? pec                 |
| NGC 3991     | 3192   | 46.   | −19.9 | Im                       |
| NGC 4670     | 1069   | 14.6  | −17.8 | SB(s)0/a pec:            |
| NGC 5253     | 404    | 4.1   | −17.4 | Amorphous/BCD            |
| Tol1924-416  | 2843   | 37.   | −19.9 | Blue compact             |
| NGC 7552     | 1585   | 19.6  | −20.2 | (R')SB(s)ab              |

Note.—Keys to columns 2 to 8 follow.

Col.2 – Heliocentric radial velocity in $\text{km s}^{-1}$. The source for the measurements is the RC3 (de Vaucouleurs et al., 1991) except for NGC 1705, MFDC; NGC 3690, Mazarella et al. (1993); Tol1924-416, Iye et al. (1987).

Col.3 – Distance in Mpc derived from $V_r$ using the linear Virgo-centric flow model of Schechter (1980) with parameters $\gamma = 2$, $V_{\text{Virgo}} = 976 \text{ km s}^{-1}$, $w_\odot = 220 \text{ km s}^{-1}$ (Binggeli et al., 1987), and $D_{\text{Virgo}} = 15.9 \text{ Mpc}$ (i.e. $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$), except for NGC 5253 for which the direct Cepheid $D$ of Sandage et al. (1994) is adopted. The solution for NGC 4670 is triple valued, we have chosen the middle value (the other solutions are $D = 11.0, 21.7 \text{ Mpc}$).

Col.4 – $B$ band absolute magnitude corrected for only Galactic extinction; i.e. $M_B = m_B - 5 \log(D/\text{1 Mpc}) - 25 - A_{B,\text{gal}}$. Both the apparent magnitudes $m_B$, and the Galactic extinction $A_{B,\text{gal}}$ (tabulated in table 2) were extracted from the NED database. The original sources are the RC3 (de Vaucouleurs et al., 1991) and Burstein & Heiles (1982, 1984), respectively.

Col.5 – Morphological classification, mostly taken from the NED data base (as of mid 1993).
Table 2
Reddening and extinction.

| Galaxy | $E(B-V)_{gal}$ | $E(B-V)_{BD}$ | $E(B-V)_{UV}$ | $E(\beta)$ | $A_{220,gal}$ | $A_{220,T}$ | $A_{B,gal}$ | $A_{H\alpha,T}$ |
|--------|----------------|---------------|---------------|------------|---------------|-------------|-------------|----------------|
| NGC 1705 | 0.044 | 0.00 (1) | 0.003 | 0.02 | 0.37 | 0.40 | 0.18 | 0.11 |
| I Zw 18 | 0.005 | 0.09 (2) | 0.004 | 0.03 | 0.04 | 0.08 | 0.02 | 0.24 |
| NGC 3310 | 0.000 | 0.23 (3) | 0.177 | 1.43 | 0.00 | 1.52 | 0.00 | 0.55 |
| NGC 3690 | 0.000 | 0.66 (4) | 0.218 | 1.76 | 0.00 | 1.86 | 0.00 | 1.58 |
| NGC 3991 | 0.005 | 0.08 (5,6) | 0.071 | 0.57 | 0.04 | 0.65 | 0.02 | 0.22 |
| NGC 4670 | 0.010 | 0.22 (7) | 0.106 | 0.85 | 0.08 | 0.99 | 0.04 | 0.53 |
| NGC 5253 | 0.044 | 0.00 (1) | 0.134 | 1.08 | 0.37 | 1.52 | 0.18 | 0.13 |
| Tol1924-416 | 0.073 | 0.02 (1) | 0.032 | 0.26 | 0.62 | 0.90 | 0.30 | 0.23 |
| NGC 7552 | 0.000 | 0.70 (1) | 0.369 | 2.98 | 0.00 | 3.13 | 0.00 | 1.68 |

Note. — $E$ denotes color excess (reddenning) in magnitudes (except for $E(\beta)$), and $A$ values are extinctions also in magnitudes. A “gal” subscript denotes reddening or extinction arising in our Galaxy, while a “T” subscript denotes total = Galactic + internal. Keys to columns 2 to 9 follow:

Col.2 – Galactic color excess $E(B-V)_{gal} = A_{B,gal}/4.1$, where $A_{B,gal}$ is the $B$ band galactic extinction listed in col.8.

Col.3 – Internal reddening (ie total - Galactic) determined from published Balmer Decrement measurements and assuming case B recombination. The numbers in parenthesis are the reference to the measurements: 1. C94; 2. Skillman &Kennicutt (1993); 3. Pastoriza et al. (1993); 4. Mazarella & Boroson (1993); 5. Osterbrock & Shaw (1988); 6. Keel et al. (1985); 7. Hunter et al. (1994b).

Col.4 – Internal reddening of $B-V$ determined from $\beta$ color excess (see col.5) calculated using the formulism in the appendix and the K94 extinction law.

Col.5 – Internal color excess in $\beta$: $E(\beta) = \beta + 2.5$, where the $\beta$ values are those in col.6 of table 4, which have been corrected for galactic extinction.

Col.6 – Foreground extinction in the F220W bandpass derived from $E(B-V)_{gal}$ using the formulism in the appendix for the Seaton (1979) extinction law.

Col.7 – Total extinction in the F220W bandpass where the internal component is derived from $E(B-V)_{UV}$ using the formulism in the appendix for the K94 extinction law.

Col.8 – Foreground $B$ band Galactic extinction, $A_{B,gal}$, from Burstein & Heiles (1984).

Col.9 – Total extinction at $H\alpha$. The Galactic component is calculated using the Seaton (1979) extinction law, while the internal component is calculated from $E(B-V)_{BD}$ using the K94 extinction law.
| Galaxy | Rootname  | R.A. (coordinate center J2000) | Dec. | Filters | UT date (d/m/y h:m) | Δt (s) |
|--------|-----------|-------------------------------|------|---------|-------------------|--------|
| NGC 1705a | x19p5101t | 04 54 13.38 | -53 21 38.5 | F220W, F1ND | 28/02/93 08:28 | 497 |
| NGC 1705b | x19p0101t | 04 54 13.41 | -53 21 38.9 | F220W, F1ND | 11/04/93 23:35 | 497 |
| IZw18    | x19p0201t | 09 34 01.91 | +55 14 27.8 | F220W | 11/03/93 11:36 | 1497 |
| NGC 3310  | x19p0301t | 10 38 45.84 | +53 30 12.5 | F220W | 17/02/93 00:00 | 197 |
| NGC 3690  | x19p0401t | 11 28 30.90 | +58 33 45.1 | F220W | 11/04/93 10:27 | 897 |
| NGC 3991  | x19p0501t | 11 57 31.77 | +32 20 31.0 | F220W | 16/02/93 17:27 | 397 |
| NGC 4670  | x19p0601t | 12 45 17.27 | +27 07 32.3 | F220W | 23/05/93 05:14 | 297 |
| NGC 5253  | x19p0701m | 13 39 55.99 | -31 38 26.6 | F220W, F1ND | 21/02/93 22:56 | 497 |
| Tol1924–416 | x19p0801t | 19 27 58.35 | -41 34 30.0 | F220W | 11/04/93 09:14 | 447 |
| NGC 7552  | x19p0901t | 23 16 10.85 | -42 35 03.0 | F220W | 07/05/93 23:04 | 997 |
Table 4
Comparison with IUE and FOS properties

| Galaxy     | $m_{220}$(FOC) (2) | $m_{220}$(IUE) (3) | $\beta_{\text{raw}}$(IUE) (4) | $\beta_{\text{raw}}$(FOS) (5) | $\beta$ (6) |
|------------|---------------------|---------------------|-------------------------------|-------------------------------|-------------|
| NGC 1705   | 11.86 ± 0.04        | 11.98 ± 0.05        | -2.40                         | -2.48                         |             |
| IZw18      | 14.49 ± 0.05        | 14.67 ± 0.15        | -2.46                         | -2.48                         |             |
| NGC 3310   | 12.08 ± 0.03        | 11.97 ± 0.18        | -1.07                         | -1.07                         |             |
| NGC 3690   | 12.97 ± 0.03        | 13.69 ± 0.18        | -1.40                         | -0.74                         | -0.74       |
| NGC 3991   | 13.13 ± 0.08        | 13.06 ± 0.10        | -1.92                         | -1.94                         |             |
| NGC 4670   | 12.57 ± 0.05        | 12.72 ± 0.06        | -1.63                         | -1.83                         | -1.63       |
| NGC 5253   | 11.75 ± 0.04        | 11.69 ± 0.08        | -1.34                         | -1.43                         |             |
| Tol1924-416| 13.25 ± 0.07        | 13.49 ± 0.08        | -2.11                         | -2.24                         |             |
| NGC 7552   | 13.14 ± 0.05        | 13.12 ± 0.19        | 0.48                          | -0.22                         | 0.48        |

Note.—Keys to columns 2 to 6 follow.

Col.2 – The apparent magnitude, $m_{220}$, extracted from the FOC images with a circular aperture having $R = 6.94''$ yielding the same area as the IUE extraction aperture of K93. The error combines the photon statistics error in the total number of counts with the uncertainty induced by changing the background level by $\pm 1\sigma$.

Col.3 – $m_{220}$ derived from the IUE spectra of K93. The error was derived by interpolating the errors reported in Table 8 of K93.

Col.4 – UV spectral slope from the IUE spectra. No corrections for reddening (either Galactic foreground or internal) have been made. Typical formal errors in $\beta$ are 0.02. However, $\beta$ is sensitive to the exact placement of the continuum windows, so more realistic errors are $\sim 0.15$ (Robert et al., 1995).

Col.5 – Same as col.4 but from the FOS spectra of Robert et al. (1995) which were obtained with a 1'' diameter aperture.

Col.6 – Adopted UV slope after correction for foreground Galactic extinction (see Table 2).
### Table 5
Surface Photometry Extraction Parameters

| Name          | $\Delta \alpha_i$ | $\Delta \delta_i$ | $a_i$ | $\phi_i$ | $\Delta \alpha_o$ | $\Delta \delta_o$ | $a_o$   | $(a/b)_o$ | $\phi_o$ |
|---------------|--------------------|--------------------|-------|----------|--------------------|--------------------|--------|----------|----------|
|               | (")               | (")               |       | (°)      | (")               | (")               |        | ("/"")  | (°)      |
| NGC1705       | 0.000             | 0.000             | 2.00  | 30.00    | -1.380            | -1.170            | 7.50   | 1.300    | 72.70    |
| IZw18         | -0.394            | -0.313            | 1.00  | -37.43   | -1.277            | -1.854            | 6.70   | 1.964    | -37.43   |
| NGC3310       | 0.000             | 0.000             | 1.50  | -52.00   | -0.640            | -1.270            | 4.50   | 1.125    | -52.00   |
| NGC3690-BC    | 1.687             | 3.157             | 1.00  | -12.10   | 1.112             | 0.778             | 5.20   | 1.480    | -12.10   |
| NGC3690-Ab    | 7.423             | -4.611            | 1.00  | 0.00     | 7.423             | -4.611            | 4.20   | 1.000    | 0.00     |
| NGC3690-Aa    | 13.292            | -3.670            | 1.00  | 0.00     | 13.292            | -3.670            | 4.20   | 1.000    | 0.00     |
| NGC3991       | 0.000             | 0.000             | 1.00  | 14.13    | 1.322             | -3.451            | 7.30   | 2.690    | 14.13    |
| NGC4670       | 0.000             | 0.000             | 1.00  | 75.60    | 2.133             | -0.967            | 4.30   | 1.830    | 75.60    |
| NGC5253       | 0.000             | 0.000             | 2.50  | 22.00    | 0.000             | 0.000             | 8.60   | 1.800    | 22.00    |
| Tol1924-416   | 0.608             | -0.090            | 1.00  | 78.70    | 0.712             | -0.344            | 4.90   | 1.870    | 93.60    |
| NGC7552       | 0.500             | -0.275            | 1.00  | 83.70    | 1.459             | -1.357            | 7.10   | 1.500    | 83.70    |

### Table 6
Surface Photometry Results

| Name               | $a_{max}$ | $a_e$ | $m_T$ | $\mu_e$ | $f_{clumpy}$ |
|--------------------|-----------|-------|-------|---------|--------------|
| NGC 1705 (total)   | 11.20     | 0.85  | 11.77 | 14.0:   | 0.52         |
| NGC 1705 (no NGC1705-1) | 11.20 | 2.75  | 12.36 | 16.51   | 0.17         |
| IZw18              | 8.75      | 1.95  | 14.45 | 17.74   | 0.05         |
| NGC 3310           | 12.60     | 7.75  | 11.08 | 17.39   | 0.07         |
| NGC 3690-BC        | 13.30     | 3.20  | 12.95 | 17.23   | 0.23         |
| NGC 3690-Ab        | 4.20      | 1.25  | 15.15 | 17.63   | 0.21         |
| NGC 3690-Aa        | 2.80      | 1.20  | 15.47 | 17.86   | 0.31         |
| NGC 3690 (sum)     | 12.73     |       |       |         | 0.24         |
| NGC 3991           | 16.45     | 4.00  | 12.86 | 17.22   | 0.14         |
| NGC 4670           | 14.00     | 3.05  | 12.46 | 16.43   | 0.18         |
| NGC 5253           | 15.40     | 6.10  | 11.43 | 16.93   | 0.21         |
| Tol1924-416        | 9.80      | 2.70  | 13.22 | 17.03   | 0.16         |
| NGC 7552           | 8.40      | 1.45  | 13.12 | 15.88   | 0.21         |
Table 7
Compact source cross-identifications.

| Our name       | Other name | Ref. | Other name | Ref. |
|----------------|------------|------|------------|------|
| NGC5253-1      | NK1        | CP89 |            |      |
| NGC5253-12     | NK2        | CP89 |            |      |
| NGC5253-2      | NK3        | CP89 |            |      |
| NGC5253-4,7    | NK4        | CP89 |            |      |
| NGC1705-1      | nucleus    | MFDC | A          | MMT  |
| NGC1705-4      | j          | MFDC |            |      |
| NGC3310-5,9    | A          | P93  | Jumbo      | BH81 |
| NGC3310-3,8    | C          | P93  |            |      |
| NGC3310-2,6    | E          | P93  |            |      |
| NGC3690-5,8    | B1         | WW91 |            |      |
| NGC3690-2      | B2         | WW91 | Ac         | MB93 |
| NGC3690-4 (Ab) | S          | F87  | Ab         | MB93 |
| NGC3690-3 (Aa) | W          | F87  | Aa         | MB93 |

References.—CP89: Caldwell & Phillips, 1989; MFDC: Meurer et al. (1992); MMT: Melnick et al. (1985); P93: Pastoriza et al., 1993; BH81: Balick & Heckman, 1981; WW91: Wynn-Williams et al. (1991); MB93: Mazarella & Boroson, 1993; F87: Friedman et al., 1987.
### Table 8

**Fluxes**

| Galaxy      | \( F_{\text{IR}} \) | \( F_{220} \) | \( F_{220,0} \) | \( F_{\text{H}\alpha,0} \) | Ref. | IRX | \( F_{\text{H}\alpha,0}/F_{220,0} \) |
|-------------|---------------------|----------------|----------------|------------------------|------|-----|----------------------------------|
| NGC 1705    | 51.2                | 235.           | 240.           | 3.51                   | 1    | -0.66 | 0.0146                           |
| I Zw18      | < 3.2               | 15.1           | 15.6           | 0.53                   | 2    | < -0.67 | 0.0336                           |
| NGC 3310    | 1490               | 311.           | 1260           | 16.0                   | 3,4  | 0.68 | 0.0128                           |
| NGC 3690    | 2840               | 68.2           | 666.           | 6.75                   | 5,6  | 1.62 | 0.0101                           |
| NGC 3991    | 89                 | 65.4           | 58.5,115       | 0.326                  | 7    | 0.13 | 0.0056                           |
| NGC 4670    | 142                | 87.4           | 202.           | 3.42                   | 8    | 0.21 | 0.0169                           |
| NGC 5253    | 1360               | 334.           | 960.           | 32.5                   | 9    | 0.61 | 0.0339                           |
| Tol1924-416 | 67.7               | 74.9           | 64.4,96.6      | 0.703                  | 10   | -0.04 | 0.0110                           |
| NGC 7552    | 3620               | 47.6           | 849.           | 3.29                   | 11   | 1.88 | 0.0039                           |

**Note.**—Fluxes are in units of \(10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} \). Keys to columns 2 to 6 follow.

- **Col.2** – The infrared flux \( F_{\text{IR}} \) is derived from the IRAS Faint Source Catalog (Moshir et al., 1990) measurements in the 60\(\mu\)m and 100\(\mu\)m bands using the definition of Helou et al. (1988, in their appendix). I Zw18 was not detected by IRAS so is given as an upper limit. NGC 3991 was not detected in the 100\(\mu\)m band; we assumed a 100\(\mu\)m flux of half the upper limit reported in the IRAS catalog. For NGC 3690, we assume that its flux is 60\% of \( F_{\text{IR}} \) for the Arp299 system, following Gehrz et al. (1983).
- **Col.3** – \( F_{220} \) is the total UV flux (\( \lambda f_\lambda \) as defined in appendix), derived from \( m_T \) in Table 6, corrected for Galactic extinction using the \( A_{220,\text{gal}} \) values in Table 2.
- **Col.4** – \( F_{220,0} \) is the UV flux corrected for Galactic and internal extinction using the \( A_{220,T} \) values in Table 2. The first flux reported for NGC 3991 and Tol1924-416 is taken for a circular aperture matching in area that of the H\(\alpha \) observations as noted below, the second flux is the total UV flux. It is the former value that is used in calculating \( F_{\text{H}\alpha,0}/F_{220,0} \). The fluxes were taken from the sources listed in col. 6 and measured through large enough of an aperture to recover most of the total flux with the exception of the NGC 3991 and Tol1924-416 data where a 4.7\('' \) diameter circular aperture and a 4\('' \) wide square aperture, respectively, were employed. Note that the I Zw18 measurement is for region “A” of Dufour & Hester (1990), the only portion imaged in this study, and that the NGC 7552 measurement is for the ring only.
- **Col.5** – \( F_{\text{H}\alpha,0} \) is the H\(\alpha \) flux corrected for extinction using the \( A_{\text{H}\alpha,T} \) value listed in Table 2. The fluxes were taken from the sources listed in col. 6 and measured through large enough of an aperture to recover most of the total flux with the exception of the NGC 3991 and Tol1924-416 data where a 4.7\('' \) diameter circular aperture and a 4\('' \) wide square aperture, respectively, were employed. Note that the I Zw18 measurement is for region “A” of Dufour & Hester (1990), the only portion imaged in this study, and that the NGC 7552 measurement is for the ring only.
- **Col.6** – Reference for \( F_{\text{H}\alpha,0} \) measurements. 1. MFDC; 2. Dufour and Hester (1990); 3. Kennicutt & Kent (1983); 4. Pastoriza et al. (1993); 5. Armus et al. (1990); 6. Friedman et al. (1987); 7. Keel et al. (1985); 8. Marlowe et al. (1995); 9. Walsh & Roy (1989); 10. Bergvall (1985); 11. Forbes et al. (1994a). The first of the two references for NGC 3310 and NGC 3690 provided a H\(\alpha \) + [N II] flux, and the second the [N II]/H\(\alpha \) ratio necessary to convert to a pure H\(\alpha \) flux.
| Name                  | $R_e$ | $R_{\text{max}}$ | $\mu_{e,0}$ | $L_{220}$ | $M_{*}$ | MSFR | MSFA$_e$ | SFA$_e$ |
|-----------------------|-------|-----------------|-------------|-----------|---------|------|---------|--------|
| NGC 1705 (total)      | 25.6  | 295             | 13.60       | 1.09      | 0.47    | 0.040| 9.4     | 52     |
| NGC 1705 (– NGC1705-1)| 81.0  | 295             | 16.11       | 0.634     | 0.27    | 0.024| 0.54    | 3.0    |
| IZw18                 | 126   | 433             | 17.66       | 0.367     | 0.16    | 0.014| 0.13    | 0.71   |
| NGC 3310              | 634   | 1093            | 15.87       | 47.9      | 21.1    | 1.79 | 0.67    | 3.7    |
| NGC 3690-BC           | 610   | 2332            | 15.37       | 70.8      | 31.2    | 2.7  | 1.1     | 5.9    |
| NGC 3690-Ab           | 267   | 896             | 15.77       | 9.33      | 4.1     | 0.35 | 0.74    | 4.1    |
| NGC 3690-Aa           | 256   | 597             | 16.00       | 7.08      | 3.0     | 0.26 | 0.60    | 3.3    |
| NGC 3690 (sum)        | 87.7  | 38.             | 3.2         |           |         |      |         |        |
| NGC 3991              | 664   | 2237            | 16.57       | 27.9      | 12.0    | 1.0  | 0.36    | 2.0    |
| NGC 4670              | 175   | 733             | 15.44       | 5.50      | 2.4     | 0.21 | 1.0     | 5.5    |
| NGC 5253              | 99.9  | 228             | 15.41       | 1.84      | 0.8     | 0.068| 1.0     | 5.7    |
| Tol1924-416           | 415   | 1292            | 16.13       | 16.2      | 7.1     | 0.61 | 0.53    | 2.9    |
| NGC 7552              | 135   | 652             | 12.75       | 39.9      | 17.1    | 1.45 | 12.0    | 66.    |

**Note.**—Keys to columns 2 to 8 follow:

Col.2 – Effective radius in pc.
Col.3 – Maximum or total radius (see text) in pc.
Col.4 – Extinction corrected mean surface brightness within $R_e$ in units of mag arcsec$^{-2}$. The $A_{220,T}$ values listed in Table 2 were used for the extinction correction.
Col.5 – UV Luminosity in the F220W band: $L_{220} = 4\pi D^2 F_{220,0}$, in units of $10^{42}$ erg s$^{-1}$, where $F_{220,0}$ is the total UV extinction corrected flux listed in Table 8.
Col.6 – Mass in stars massive stars, that is those with $5 \leq m_*/M_\odot \leq 100$ assuming a Salpeter (1955) calculated from $L_{220}$ as explained in the text. Units are $10^6 M_\odot$.
Col.7 – Massive star formation rate, that is the rate of formation of stars with $5 \leq m_*/M_\odot \leq 100$ assuming a constant star formation rate. Units are $M_\odot$ yr$^{-1}$.
Col.8 – Mean massive star formation rate per area within $R_e$ in units of $M_\odot$ Kpc$^{-2}$ yr$^{-1}$. Col.9 – Star formation rate per area within $R_e$ for stars with $0.1 \leq m_*/M_\odot \leq 100$, in units of $M_\odot$ Kpc$^{-2}$ yr$^{-1}$. 
| Object          | $\Delta \alpha$ (\arcsec) | $\Delta \delta$ (\arcsec) | $m_{220}$ (mag) | $M_{220}$ (mag) | $R_e$ (pc) | Notes |
|-----------------|---------------------------|---------------------------|-----------------|-----------------|-----------|-------|
| NGC5253-1       | 0.00                      | 0.00                      | 17.56 $\pm$ 0.14 | $-13.8$         | 2.0       | a,c,d |
| NGC5253-2       | 0.76                      | $-4.34$                   | 17.07 $\pm$ 0.06 | $-13.4$         | 1.5       | c     |
| NGC5253-3       | $-6.95$                   | $-6.58$                   | 18.08 $\pm$ 0.11 | $-12.7$         | 1.8       | c     |
| NGC5253-4       | $-5.01$                   | $-2.25$                   | 17.59 $\pm$ 0.06 | $-12.5$         |           |       |
| NGC5253-5       | 0.67                      | $-0.41$                   | 17.31 $\pm$ 0.05 | $-12.5$         | $\leq$ 0.7 | d     |
| NGC5253-6       | 5.46                      | 6.36                      | 17.54 $\pm$ 0.06 | $-12.4$         | 0.8       | b     |
| NGC5253-7       | $-4.36$                   | $-1.81$                   | 18.61 $\pm$ 0.11 | $-12.3$         | 1.8       |       |
| NGC5253-8       | $-2.89$                   | 2.41                      | 18.40 $\pm$ 0.11 | $-12.1$         | 1.3       |       |
| NGC5253-9       | 6.49                      | $-0.45$                   | 17.96 $\pm$ 0.06 | $-12.1$         | $\leq$ 0.7 | d     |
| NGC5253-10      | $-0.19$                   | 0.64                      | 17.56 $\pm$ 0.06 | $-12.1$         | $\leq$ 0.7 | d     |
| NGC5253-11      | $-0.62$                   | $-6.03$                   | 18.00 $\pm$ 0.08 | $-12.1$         | 1.0       |       |
| NGC5253-12      | 0.91                      | 2.52                      | ...             | $-12.1$         | 2.9       | o     |
| NGC5253-16      | 8.06                      | 4.84                      | 18.18 $\pm$ 0.07 | $-11.6$         | $\leq$ 0.7 |       |
| NGC5253-26      | 0.48                      | 7.98                      | 18.52 $\pm$ 0.08 | $-11.2$         | $\leq$ 0.7 | e     |
| NGC5253-43      | $-4.09$                   | 3.78                      | 18.70 $\pm$ 0.09 | $-10.9$         | $\leq$ 0.7 | e     |
| NGC5253-93      | 0.79                      | 10.71                     | 19.49 $\pm$ 0.13 | $-10.2$         | $\leq$ 0.7 | e     |
| NGC1705-1       | 0.00                      | 0.00                      | 12.72 $\pm$ 0.00 | $-16.6$         | 1.1       | a,h   |
| NGC1705-2       | $-0.60$                   | $-0.72$                   | 16.05 $\pm$ 0.03 | $-13.6$         | 1.2       |       |
| NGC1705-3       | 0.79                      | 1.31                      | 18.49 $\pm$ 0.08 | $-11.4$         | 1.4       | f     |
| NGC1705-4       | 0.96                      | 3.29                      | 19.19 $\pm$ 0.10 | $-10.9$         | 1.8       |       |
| NGC1705-6       | $-1.06$                   | $-0.46$                   | 18.31 $\pm$ 0.12 | $-10.7$         | $\leq$ 1.0 | f     |
| NGC1705-8       | $-3.15$                   | $-5.30$                   | 19.12 $\pm$ 0.09 | $-10.5$         | 1.4       | b     |
| NGC1705-9       | 1.30                      | $-2.72$                   | 19.11 $\pm$ 0.09 | $-10.4$         | $\leq$ 1.0 | d     |
| NGC1705-12      | 4.36                      | $-1.82$                   | 19.07 $\pm$ 0.08 | $-10.2$         | $\leq$ 1.0 | e     |
| NGC1705-15      | $-6.55$                   | $-6.14$                   | 19.34 $\pm$ 0.09 | $-10.2$         | 1.1       |       |
| NGC1705-17      | $-4.15$                   | $-5.04$                   | 19.22 $\pm$ 0.09 | $-10.2$         | ...       | g     |
| NGC1705-25      | $-1.88$                   | 3.38                      | 19.28 $\pm$ 0.09 | $-9.9$          | $\leq$ 1.0 | g     |
| NGC1705-46      | 1.87                      | 5.59                      | 19.81 $\pm$ 0.11 | $-9.4$          | $\leq$ 1.0 | e     |
| I Zw18-1        | 0.00                      | 0.00                      | 19.50 $\pm$ 0.07 | $-11.8$         | 3.2       | a     |
| I Zw18-2        | 0.78                      | $-0.86$                   | 20.22 $\pm$ 0.12 | $-11.4$         | 4.2       | d     |
| I Zw18-3        | 1.22                      | $-0.39$                   | 20.11 $\pm$ 0.10 | $-11.3$         | 4.1       | d     |
| I Zw18-4        | 3.82                      | $-4.75$                   | 20.70 $\pm$ 0.11 | $-10.8$         | 3.7       | c     |
| I Zw18-5        | 0.84                      | $-0.48$                   | 20.06 $\pm$ 0.09 | $-10.8$         | $\leq$ 2.4 | d     |
| I Zw18-6        | 1.85                      | $-0.64$                   | 20.78 $\pm$ 0.11 | $-10.3$         | 2.5       |       |
| I Zw18-10       | 0.28                      | $-0.50$                   | 20.66 $\pm$ 0.13 | $-10.1$         | $\leq$ 2.4 |       |
| I Zw18-12       | 0.58                      | $-1.05$                   | 20.59 $\pm$ 0.12 | $-9.9$          | $\leq$ 2.4 | d     |
| NGC4670-1       | 0.00                      | 0.00                      | 16.57 $\pm$ 0.04 | $-15.1$         | $\leq$ 2.4 | a,b   |
| NGC4670-2       | 0.11                      | $-0.38$                   | 17.20 $\pm$ 0.08 | $-14.8$         | 3.4       | b     |
| NGC4670-3       | $-1.92$                   | $-1.91$                   | 17.02 $\pm$ 0.04 | $-14.8$         | $\leq$ 2.4 | d     |
| NGC4670-4       | $-2.01$                   | $-1.16$                   | 17.29 $\pm$ 0.05 | $-14.5$         | $\leq$ 2.4 | b     |
| NGC4670-5       | $-5.13$                   | $-1.21$                   | 17.38 $\pm$ 0.05 | $-14.4$         | $\leq$ 2.4 | c     |

Table 10

Compact sources
| Object         | $\Delta \alpha$ ($''$) | $\Delta \delta$ ($''$) | $m_{220}$ (mag) | $M_{220}$ (mag) | $R_e$ (pc) | Notes |
|---------------|--------------------------|------------------------|----------------|----------------|-----------|-------|
| NGC4670-6     | −1.29                    | −1.61                  | 17.44 ± 0.05   | −14.4          | ≤ 2.4     |       |
| NGC4670-7     | −0.29                    | 0.35                   | 17.95 ± 0.08   | −14.3          | 3.5       |       |
| NGC4670-8     | −2.10                    | −2.17                  | 17.68 ± 0.06   | −14.1          | 3.1       | b     |
| NGC4670-9     | −5.06                    | −1.63                  | 17.76 ± 0.05   | −14.1          | ≤ 2.4     |       |
| NGC4670-10    | −2.24                    | −2.51                  | 18.17 ± 0.07   | −13.8          | 2.6       |       |
| NGC4670-21    | −10.74                   | −1.76                  | 19.37 ± 0.10   | −12.4          | ...       |       |
| NGC3310-1     | 0.00                     | 0.00                   | 16.13 ± 0.03   | −16.6          | ≤ 3.0     | d     |
| NGC3310-2     | −3.38                    | 11.01                  | 17.28 ± 0.05   | −15.7          | ≤ 3.0     | c     |
| NGC3310-3     | 0.10                     | 7.35                   | 17.46 ± 0.05   | −15.4          | ≤ 3.0     |       |
| NGC3310-4     | −2.13                    | −1.14                  | 17.69 ± 0.06   | −15.1          | ≤ 3.0     |       |
| NGC3310-5     | −15.02                   | −0.96                  | 18.39 ± 0.10   | −14.7          | 3.2       |       |
| NGC3310-6     | −2.98                    | 10.59                  | 18.26 ± 0.08   | −14.6          | 3.2       |       |
| NGC3310-7     | −9.41                    | 5.53                   | 18.43 ± 0.09   | −14.6          | 3.7       |       |
| NGC3310-8     | −0.03                    | 6.83                   | 18.60 ± 0.10   | −14.6          | 4.1       |       |
| NGC3310-9     | −14.24                   | −1.50                  | 18.51 ± 0.12   | −14.4          | ≤ 3.0     | d     |
| NGC3310-10    | −11.03                   | −4.08                  | 18.76 ± 0.09   | −14.3          | 3.7       |       |
| NGC7552-1     | 0.00                     | 0.00                   | 16.47 ± 0.02   | −18.1          | ≤ 3.2     | a     |
| NGC7552-2     | 0.48                     | −0.66                  | 16.75 ± 0.04   | −17.9          | ≤ 3.2     | j     |
| NGC7552-3     | −0.29                    | 0.21                   | 17.14 ± 0.05   | −17.7          | 3.5       |       |
| NGC7552-4     | −0.84                    | −0.68                  | 17.56 ± 0.05   | −17.3          | 4.0       |       |
| NGC7552-5     | −1.11                    | −0.35                  | 18.06 ± 0.08   | −17.0          | 4.5       |       |
| NGC7552-6     | −4.34                    | −2.51                  | 18.49 ± 0.04   | −16.1          | ≤ 3.2     |       |
| NGC7552-13    | −2.47                    | −2.09                  | 20.21 ± 0.10   | −14.4          | ...       |       |
| NGC7552-25    | −2.81                    | −1.63                  | 20.96 ± 0.16   | −13.6          | ...       |       |
| TOL1924-416-1 | 0.00                     | 0.00                   | 16.71 ± 0.04   | −17.3          | ≤ 6.2     | a,c,d |
| TOL1924-416-2 | −11.72                   | −4.81                  | 17.58 ± 0.04   | −16.2          | ≤ 6.2     | d,k   |
| TOL1924-416-3 | 1.36                     | −2.61                  | 17.89 ± 0.05   | −15.9          | ≤ 6.2     |       |
| TOL1924-416-4 | −0.87                    | −0.61                  | 18.05 ± 0.05   | −15.9          | ≤ 6.2     | d     |
| TOL1924-416-5 | −5.43                    | −0.47                  | 18.32 ± 0.06   | −15.8          | 8.6       |       |
| TOL1924-416-6 | −1.11                    | −0.40                  | 18.29 ± 0.06   | −15.7          | 6.7       | d     |
| TOL1924-416-7 | −3.41                    | −0.42                  | 19.31 ± 0.10   | −15.6          | 16.7      |       |
| TOL1924-416-8 | −1.36                    | −0.92                  | 18.85 ± 0.08   | −15.0          | ≤ 6.2     |       |
| TOL1924-416-9 | −2.57                    | −0.04                  | 19.18 ± 0.08   | −14.7          | ≤ 6.2     |       |
| TOL1924-416-10| −0.21                    | 0.13                   | 19.41 ± 0.17   | −14.3          | ...       |       |
| TOL1924-416-11| 2.40                     | −1.68                  | 19.45 ± 0.10   | −14.3          | ...       |       |
| TOL1924-416-12| −11.46                   | −4.76                  | 19.57 ± 0.09   | −14.2          | ...       |       |
| TOL1924-416-13| −1.35                    | 0.76                   | 19.62 ± 0.12   | −14.1          | ...       |       |
| TOL1924-416-14| −4.14                    | −0.11                  | 19.69 ± 0.14   | −14.0          | ...       |       |
| NGC3690-1     | 0.00                     | 0.00                   | 16.57 ± 0.02   | −18.5          | ≤ 7.4     | a     |
| NGC3690-2     | −0.49                    | −2.02                  | 17.32 ± 0.04   | −18.3          | 10.9      |       |
| NGC3690-3     | −13.29                   | −3.68                  | 17.05 ± 0.04   | −18.0          | ...       | i     |
| Object       | \(\Delta \alpha\) (") | \(\Delta \delta\) (") | \(m_{220}\) (mag) | \(M_{220}\) (mag) | \(R_e\) (pc) | Notes |
|--------------|-------------------------|-------------------------|-------------------|-------------------|--------------|-------|
| NGC3690-4    | -7.42                   | -4.62                   | 17.75 ± 0.04      | -17.7             | 10.6         | d     |
| NGC3690-5    | 0.56                    | -4.97                   | 17.53 ± 0.04      | -17.6             | ...          | l     |
| NGC3690-6    | -2.06                   | 4.30                    | 18.26 ± 0.06      | -17.3             | 12.8         | b     |
| NGC3690-7    | -2.88                   | 3.65                    | 18.07 ± 0.04      | -17.3             | \(\leq 7.4\) | j     |
| NGC3690-8    | 0.51                    | -4.84                   | 18.01 ± 0.06      | -17.1             | ...          | l     |
| NGC3690-9    | -3.39                   | 1.98                    | 18.31 ± 0.04      | -16.8             | \(\leq 7.4\) |       |
| NGC3690-10   | -3.16                   | 1.37                    | 18.81 ± 0.06      | -16.6             | 7.9          |       |
| NGC3690-11   | -13.12                  | -5.16                   | 19.08 ± 0.06      | -16.5             | 11.4         | k     |
| NGC3690-12   | -1.88                   | 2.32                    | 19.01 ± 0.07      | -16.1             | ...          | m     |
| NGC3690-13   | -1.91                   | 2.54                    | 19.22 ± 0.08      | -15.9             | ...          | m     |
| NGC3690-14   | -2.92                   | 2.15                    | 19.26 ± 0.09      | -15.8             | ...          |       |
| NGC3690-15   | -1.36                   | 4.68                    | 19.35 ± 0.08      | -15.8             | ...          |       |
| NGC3690-16   | -4.55                   | 1.14                    | 19.49 ± 0.07      | -15.6             | ...          |       |
| NGC3991-1    | 0.00                    | 0.00                    | 17.06 ± 0.05      | -17.5             | 12.4         | a,b   |
| NGC3991-2    | -0.58                   | -0.85                   | 19.12 ± 0.15      | -16.2             | 21.0         | c     |
| NGC3991-3    | -1.75                   | -6.05                   | 19.02 ± 0.09      | -15.4             | 10.7         | b     |
| NGC3991-4    | 0.27                    | 0.42                    | 19.42 ± 0.14      | -15.3             | 15.7         |       |
| NGC3991-5    | -1.33                   | -2.75                   | 18.80 ± 0.09      | -15.2             | ...          | n     |
| NGC3991-6    | -1.22                   | -2.54                   | 19.28 ± 0.11      | -14.7             | ...          | n     |
| NGC3991-7    | -4.71                   | -5.42                   | 19.69 ± 0.11      | -14.7             | 11.5         |       |
| NGC3991-8    | -1.62                   | -0.92                   | 19.95 ± 0.16      | -14.5             | 15.7         | b     |
| NGC3991-9    | -1.10                   | -2.45                   | 19.70 ± 0.15      | -14.3             | ...          |       |
| NGC3991-10   | -0.86                   | -2.67                   | 19.99 ± 0.16      | -14.3             | 11.6         | d     |
Table 10—Continued

| Object | ∆Notes |
|--------|--------|
|        |        |
| (1)    |        |

Note.—Keys to columns 2 – 7 follow.
Col.2,3 – The position offsets relative to the coordinates given in table 3. These relative positions should be accurate to about 30 mas (P. Hodge, private communication, 1994) with the exception of the images of NGC 1705a, and Tol1924-416. These exposures were initiated 1.5 hours after FOC turn on, which is considered to be too soon for the geometric distortions to fully stabilize. A comparison of matched positions in the two NGC 1705 frames yields a dispersion of 80 mas (3.5 pixels) in relative offsets.
Col.4 – The apparent magnitude, derived from the aperture photometry, with no correction for the size of the object. The errors are the random errors due to photon statistics. An additional quasi-random uncertainty of $\sim 0.15$ mag is expected due to positional variations in the photometric performance of the FOC (Meurer, 1995).
Col.5 – Absolute magnitudes derived from the profile fitting where available, otherwise from the aperture photometry.
Col.6 – Effective or half light radius determined from profile fitting. Sources not fitted are indicated with an ellipses (…).
Col.7 – Notes on the individual sources as follow: (a) Coordinate system origin for the galaxy. (b) Elongated or double in appearance. (c) Elliptical shape. (d) Neighbor with $10 < r < 14$ pixels. (e) Selected as probable star. (f) Low signal/noise because of NGC1705-1 subtraction. (g) $\Delta m_{220} > 0.4$ mag between NGC 1705 frames. (h) $R_e$ from PC image. See text. (i) At edge of thin occulting finger. (j) Reseau within fitting area. (k) Near edge of frame. (l) Double source NGC3690-5/8. (m) Double source NGC3690-12/13. (n) Double source NGC3991-5/6. (o) very diffuse, not found by DAOFIND. Fit out to $r = 15.5$ pixels.
Table 11
AVERAGE QUANTITIES FOR IONIZING POPULATIONS.

| quantity     | ISB | CSF |
|--------------|-----|-----|
|              | avg | min | max | avg | min | max |
| 220 − V      | −2.53 | −2.92 | −0.95 | −2.38 | −2.88 | −1.63 |
| RL           | −0.003 | −0.008 | 0.002 | −0.001 | −0.003 | 0.002 |
| NC           | 0.14 | 0.00 | 0.31 | 0.17 | 0.08 | 0.33 |
| 0.31         | 0.25 | 0.34 | |
| β            | −2.52 | −2.70 | −2.26 | −2.51 | −2.65 | −2.32 |
| log(L_{220}/L_T) | −0.48 | −0.61 | −0.41 | −0.50 | −0.58 | −0.46 |
| log(M/L_{220}) (m_l = 5 M⊙) | −2.96 | −3.24 | −2.37 | −2.78 | −3.10 | −2.13 |
| log(M/L_{220}) (m_l = 1 M⊙) | −2.62 | −2.90 | −2.04 | −2.46 | −2.76 | −1.80 |
| log(M/L_{220}) (m_l = 0.1 M⊙) | −2.22 | −2.50 | −1.63 | −2.04 | −2.35 | −1.39 |

Table 12
EFFECTS OF DIFFERENT REDDENING LAWS.

| law             | r_β | a_0   | a_1   | a_2  | a_3  | rms  |
|-----------------|-----|-------|-------|------|------|------|
| Galactic        | 1.793 | 8.519 | −0.647 | −0.103 |     | 0.014 |
| LMC             | 6.896 | 8.069 | −0.309 | −0.105 |     | 0.012 |
| Starburst (K94) | 8.067 | 8.613 | −0.370 | 0.035 | −0.085 | 0.015 |
| Starburst (C94) | 4.326 | 6.956 | −0.097 | −0.024 |     | 0.006 |