THE STRUCTURE AND MORPHOLOGY OF THE IONIZED GAS IN STARBURST GALAXIES: NGC 5253/5236

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ABSTRACT

We investigate the interplay between starbursts and host galaxies by studying the structure and physical characteristics of the ionized gas surrounding the central starbursts in the two nearby galaxies NGC 5253 and NGC 5236. The two systems form a pair that presumably interacted about 1 Gyr ago. They represent very different galactic environments, NGC 5253 being a metal-poor dwarf and NGC 5236 being a metal-rich, massive, grand-design spiral. We present images of the starburst regions in these two galaxies in the light of the line emission [O iii], Hα, and [S ii] and in continuum $U$, $V$, and $R$.

For NGC 5253, the images are deep enough that we can detect faint Hα arches and filaments out to $\sim 1.9$ kpc and [S ii] filaments out to $\sim 1$ kpc from the main ionizing cluster. The ground-based line images are complemented with an archival HST Wide Field Planetary Camera 2 H$\beta$ image. Line ratio maps $[O\ iii]/H\beta$ and $[S\ ii]/H\alpha$ show that in the outer regions the diffuse ionized gas is partially excited by a nonphotoionization process (“shocks”). The “shocked” gas is mostly concentrated southwest of the galaxy’s center, in coincidence with the position of Hα bubbles and with extended soft X-ray emission. The Hα emission from the shock-excited gas is $\approx 1\%\text{--}2\%$ of the total and $\approx 10\%\text{--}20\%$ of the diffuse ionized gas emission, although the mechanical input from the starburst would be sufficient to support a shocked Hα luminosity $\sim 3$ times the observed one. About $80\%\text{--}90\%$ of the diffuse gas is consistent with being photoionized, requiring that about $10\%$ of the ionizing photons escape from the starburst site. The starburst in NGC 5253 appears to be fed by gas infalling along the galaxy’s optical minor axis, while hot gas expanding from the starburst has a preferential direction along the major axis.

The results for NGC 5236 are less clear than for NGC 5253, as the images are not as deep. In the central region of NGC 5236, the Hα image traces the $U$ emission from the ionizing stars more closely than in NGC 5253; the emission-line ratio maps show very little or no evidence for presence of shock excitation. Very little or no ionized gas appears expanding from the center of the galaxy outward along the disk plane, and ionization is a local process. The starburst in NGC 5236 is thus more strongly confined than that in NGC 5253; the deeper gravitational-potential well of the more massive galaxy probably keeps the ionized gas near to the ionizing stars.

Key words: galaxies: starburst — galaxies: individual (NGC 5253, NGC 5236) — galaxies: interactions — galaxies: ISM — ISM: structure
massive stars, the DIG can extend over 10 times larger spatial scales than the ionizing stars (Reynolds 1991), and, as a result, the mechanism of ionization of the DIG is still a matter of debate. Photoionization from OB stars appears to be a general mechanism for exciting the DIG (Ferguson et al. 1996b; Ferguson, Wyse, & Gallagher 1996a; Hunter & Gallagher 1997). This requires that more than 20%–30% of the ionizing photons leak out of H II regions. However, the emission-line ratios of the DIG are often very different from what is expected from photoionization, and evidence has been accumulating in favor of mixed photoionization/shock, or some other, heating mechanism for the DIG (Sivan, Sta Isabel, & Lequeux 1986; Gallagher & Hunter 1990; Martin 1997; Rand 1998).

The DIG may be composed of at least two phases: a quiescent one, which comprises 80% of the Hz emission and has a scale height comparable to that of stars, and a turbulent one, with a scale height about 3 times that of stars (Wang 1998; Wang, Heckman, & Lehner 1997). These studies demonstrate that the effects of the massive stars extend to galactic scales and could affect the subsequent evolution of the galaxy. Star formation in starburst galaxies proceeds at a pace that is 1–2 orders of magnitude higher than in “quiescent” galaxies and thus has a major impact on the DIG, as seen in its kinematics, spatial distribution, and ionization (e.g., Marlowe et al. 1995). However, the details are not yet clear as to how the properties of the DIG correlate with the star formation rate (SFR) of the host galaxy. For instance, does the importance of the DIG increase in a starburst relative to a quiescent galaxy, or does the DIG simply become brighter and, therefore, easier to observe (Wang et al. 1998)?

To date, studies of the physical conditions of the ionized ISM in galaxies, and in starbursts in particular, have been pursued mainly via long-slit spectroscopy of a limited number of regions. However, structurally complex objects like starbursts cannot be unraveled without fully accounting for the morphology of both gas and stars. A complementary approach is to use narrow- and broadband imaging to obtain a complete map of the gas emission. While the advantage of imaging is to characterize fully the spatial distribution of the ionized gas, the disadvantage is that only the brightest ionized lines can be reasonably imaged with sufficient depth. In addition, the matching of the narrow-filter passband with the redshift of the galaxy represents a technical difficulty for large samples of galaxies. Imaging and long-slit spectroscopy provide complementary approaches to the study of the ionized gas in galaxies.

Here we present images of the two nearby starburst galaxies NGC 5253 ($v = 404$ km s$^{-1}$) and NGC 5236 ($v = 516$ km s$^{-1}$) in the light of [O III], Hz, and [S II]. Variations of the intensity of ionization lines, especially the low-ionization ones such as [S II], are direct indicators of changing physical conditions of the gas. The two galaxies form a binary pair in the Centaurus group at a distance of a few megaparsec (4 Mpc for NGC 5253; Sandage et al. 1994). They have completely different characteristics: NGC 5253 is a peculiar dwarf (Caldwell & Phillips 1989), and NGC 5236 is a massive, grand-design spiral, classified as an SABc (Telesco, Dressel, & Wolsencraft 1993); the two form a metal-poor-metal-rich pair, with NGC 5253 at about 0.5 $Z_\odot$ and NGC 5236 at about 2 $Z_\odot$. They are both experiencing a high-intensity burst of star formation in their central regions, possibly triggered by an encounter between the two about 1 Gyr ago. This possibility was first suggested by van den Bergh (1980) on the basis of various evidence, including the warping of the H I disk of NGC 5236 (Rogstad, Lockhart, & Wright 1974). Thanks to their closeness, these galaxies are excellent laboratories for studying spatial variations of the gas conditions in starbursts; 1” corresponds to a linear scale of 19 pc in NGC 5253, the size of a typical H II region.

NGC 5253 is a “benchmark starburst,” with centrally concentrated recent star formation superimposed on an older, quiescent stellar population. The central star-forming region is very blue, although it is crossed by dust lanes that produce patchy and heavy obscuration and make this galaxy at the same time an excellent UV and far-IR emitter (Kinney et al. 1993; Aitken et al. 1982; Telesco et al. 1993; Walsh & Roy 1989; Calzetti et al. 1997). Radio observations reveal that a large fraction of the most recent star formation is hidden by dust (Turner, Ho, & Beck 1998). The bulk of the ongoing starburst is located in an area 50–60 pc in size, where the stars are about 5 Myr old. The UV emission in this area is dominated by a ~3–4 Myr–old stellar cluster, but the ionization is being driven by a ~2 Myr–old, dust-buried central cluster (Calzetti et al. 1997; Crowther et al. 1999). The SFR density of ~10$^{-2}$ $M_\odot$ yr$^{-1}$ pc$^{-2}$ corresponds to the maximum levels observed in star-forming galaxies (Meurer et al. 1997). Extending beyond the starburst is a ~300 pc region where star formation has been active at a roughly constant level for the last ~100 Myr, with a SFR density about 0.01 of that of the starbursts; a handful of bright stellar clusters with ages between 10 and 60 Myr is contained in this area (Calzetti et al. 1997). The ionized gas around the starburst is slowly expanding, with a velocity ~10 km s$^{-1}$, at least within the inner 200 pc region (Martin & Kennicutt 1995; see also Strickland & Stevens 1999). The H II emission extends for greater than 1 kpc from the center, with two identified kiloparsec-scale superbubbles in the western periphery, one of them expanding with a velocity of 35 km s$^{-1}$ (Marlowe et al. 1995). Moderately high [O III]/Hz ratios in the presence of high [S II]/Hz ratios up to ~40” (800 pc) from the center suggest that shocks or some mechanism other than photoionization contribute to the gas excitation (from long-slit spectroscopy; see Martin 1997). The peculiar H I kinematic indicates rotation about the major axis of the galaxy (Kobulnicky & Skillman 1995), but an alternative interpretation, that NGC 5253 has accreted/is accreting relatively unprocessed gas along the minor axis, has been suggested to account for the unusually low CO luminosity (Turner, Beck, & Hurt 1997).

The starburst in NGC 5236 is comparable in intensity to the spectacular event in NGC 5253. The central star formation extends for ~20” across (~360 pc at 3.7 Mpc distance), and is bright at all wavelengths, ranging from X-ray (Trinchieri, Fabbiano, & Paulumbo 1985; Ehle et al. 1998), through the UV (Bohlin et al. 1983; Kinney et al. 1993), optical, near-IR (Gallais et al. 1991; Rouan et al. 1996), and mid-IR (Telesco et al. 1993), to the radio (Turner & Ho 1994). The nucleus proper is luminous in the near-IR owing to the large dust obscuration in the center of the galaxy (Gallais et al. 1991; Rouan et al. 1996). Large amounts of dust are present and form multiple dark lanes that surround the center and cross it in the north-south direction. Gas inflow along the bar collecting at the inner Lindblad resonance may be fueling the central starburst (Petitpas &
Wilson 1998). An optically visible arc of star formation, possibly the main source of the starburst’s UV emission, lies about 6° south and southwest of the nucleus (Heap et al. 1993; Bohlin et al. 1983). In HST Wide Field Planetary Camera (WFPC) 1 U-band observations, the arc breaks down into a series of very young star clusters, with ages of ~2–6 Myr. The arc-shaped structure could be part of a ring surrounding the nucleus where the other sections are not currently actively forming stars (Gallais et al. 1991). Perhaps star formation has not been coeval but sequential, propagating through the ring. Differences between the BY EW and CO EW maps support this picture (Puxley et al. 1997). Mid-IR (Telesco et al. 1993) and radio (Turner & Ho 1994) maps depict a different picture. These show two main sources amid diffuse emission: the northern-most source coincides with an optical clump about 11″ northwest of the nucleus and slightly west of the central dust lane, while the southern one is obscured at shorter wavelengths by the dust lane in which it appears to be embedded (Telesco et al. 1993). The detection of only two “pointlike” sources at long wavelengths led various authors to advocate their extreme youth.

Whatever the processes that triggered the central starbursts in the two galaxies, they were acting on two very different environments: a grand-design, massive spiral galaxy in NGC 5236 and a dwarf in NGC 5253. One candidate for the triggering perturbation is the encounter between the two galaxies about 1 Gyr ago (van den Bergh 1980); if this is the case, the timing of the trigger is the same. This would reduce by one the number of free parameters in the problem. The difference between the two environments would then be the major variable, making this pair an important test bed for starburst studies. This paper therefore focuses on the role of the host galaxy environment on the evolution of the starburst by investigating the physical properties and variations of the large-scale structure of the ionized medium associated with each of the two starbursts. Section 2 describes the observations and data reduction; §3 presents the analysis of the observations, with special emphasis on nebular line emission; the discussion is contained in §4 and the conclusions in §5.

### 2. OBSERVATIONS AND DATA REDUCTION

Broad- and narrowband images of NGC 5253 (Fig. 1) and NGC 5236 (Fig. 2) were obtained at the 2.5 m telescope of Las Campanas Observatory with the Direct Camera and a 2K × 2K CCD during the nights of 1997 April 28–May 1. Broadband images were obtained with 3 inch × 3 inch (7.6 cm × 7.6 cm) filters in the Harris U, V, and R. Narrowband images were obtained using 2 inch × 2 inch (5 cm × 5 cm) filters on loan from Cerro Tololo Inter-American Observatory centered at the redshifted wavelengths of [O III] λλ4959, 5007, Hα + [N ii] λλ6548, 6584, and [S II] λλ6717, 6731 (see Table 1). The plate scale on the CCD is 0.26 pixel⁻¹, implying a total field of view of 8.8 for the broadband images. The small size of the narrowband filter introduced vignetting at the edges of the CCD, and the final unvignetted field of view was about 52″; the presence of scattered light from the edges of the filters further reduced the useful field of view of the narrowband images to about 47″. The seeing varied during the course of the four nights in the range 0.9–1.2.

Given the surface brightness variation of more than a factor of 100 from the center to the edges of the starburst regions (and more than a factor of 10,000 in line emission intensity), the exposure times ranged from 30 to 600 s in V and R and from 30 to 1200 s in U and in the narrowband filters to achieve suitable exposure levels in different regions of the galaxies. Offsets of a few arcseconds between frames were introduced to remove cosmic defects (bad pixels and two central bad columns) from the final combined images. Table 2 lists for both galaxies the total exposure time in each filter.

Data reduction followed the standard procedure of bias subtraction, flat-fielding, registration, and co-addition of the images. Both dome and twilight exposures were used to remove pixel-to-pixel variations and illumination patterns from the images. Residual scattered light in the [S II] filter was removed by subtracting a surface fit to the background. The background fit for NGC 5253 was adopted for both galaxies, since the background of NGC 5236 could not be fitted as this galaxy completely fills the field of view. The two central bad columns of the chip were linearly interpolated in each image with values from surrounding columns. Cosmic rays were removed from individual frames before co-addition, using an algorithm developed by M. Dickinson (1997, private communication) for the identification of sharp, positive discontinuities over scales of ~1 pixel. This technique removed around 80%–90% of the cosmic rays; final co-addition of multiple frames removed

### Table 1

**Table 1**

| Filter   | λ* (Å) | FWHM (Å) | Flux Conversion (ergs cm⁻² Å⁻¹ ADU⁻¹) | Detection Limit (ergs cm⁻² arcsec⁻²) |
|----------|--------|----------|------------------------------------|-------------------------------------|
| Harris U | 2.139E18 (5%) | 4.6E-20 |
| Harris V | 2.550E19 (2%) | 4.3E-20 |
| Harris R | 1.106E19 (1.5%) | 3.6E-20 |
| 5000/70 | 4994 | 77 | 4.97E-18 (4%) | 7.4E-18 |
| 6565/78 | 6568 | 68 | 2.36E-18 (3%) | 8.0E-18 |
| 6737/76 | 6747 | 91 | 1.79E-18 (3%) | 9.3E-18 |

*a Central wavelength of the narrowband filters.
*b Flux zero point is given with, in parentheses, the internal uncertainty.
*c Limiting surface brightness is in ergs cm⁻² arcsec⁻² for the continuum-subtracted narrowband images ([O III], Hα, and [S II]), and it is a surface brightness density in ergs cm⁻² arcsec⁻² Å⁻¹ for the broadband images. The values refer to 1 e-detection limits of the deepest images obtained in this project (see Table 2), rebinned to a resolution of 1.3, namely, 5 × 5 pixels².
most of the remaining events. Both galaxies were observed close to their culminating points, and the effects of air-mass variations were generally less than 3%; exceptions were $U$ and $[\text{O III}]$, where such effects were as large as 12% and 5%, respectively, and corrections were therefore applied. Absolute calibrations were obtained from observations of two spectrophotometric standards from Hamuy et al. (1994). One of the standards was also observed during the night at different azimuths to derive air-mass corrections. Absolute flux calibrations are listed in Table 1 for all filters, together with the internal error (in percentage).

2.1. Emission-Line Images

More than one emission line is included in each of the three narrowband filters. Both the redshifted $[\text{O III}]$ λ4959 and $[\text{O III}]$ λ5007 contribute to the emission in the 5000/70 filter; the second line is located almost at the center of the passband, while the $[\text{O III}]$ λ4959 is located on the

Fig. 1.—Comparison of the $R$-band (top panel) and the continuum-subtracted $H_\alpha + [\text{N II}]$ (bottom panel) images of NGC 5253 shows the extent of the ionized gas emission. North is up, and east is left. Arcs and filaments of ionized gas are evident especially in the southwest region. Each image covers a field of view of 3.36 in size. Both images are among the deepest in our set, and their central few arcseconds are saturated.

800 CALZETTI ET AL. Vol. 118
Fig. 2.—$R$-band (a) and the continuum-subtracted $H\alpha + [N\,\text{II}]$ (b) images of NGC 5236 are shown together with the $[S\,\text{II}] \lambda\lambda 6717, 6731/H\alpha$ line ratio map (c). Here the $H\alpha + [N\,\text{II}]$ emission runs along the two spiral arms departing from the center of the galaxy. Unlike the other galaxy, the ionized gas emission in NGC 5236 shows little evidence for presence of arcs, filaments, or other complex structures. The $[S\,\text{II}]/H\alpha$ line ratio image also traces the central burst of star formation and the star-forming spiral arms. The gray scale in (c) marks values from a minimum of $[S\,\text{II}]/H\alpha \simeq 0.1$ (light gray) up to $[S\,\text{II}]/H\alpha \simeq 1.5$ (dark gray/black). The third panel has been resampled to 5 pixel $\times$ 5 pixel bins. North is up, and east is left. Each image covers a field of view of 5.20 $\prime$.20.

ramp, making the determination of its contribution rather uncertain. Our estimates give a best value of $\sim 95\%$ for the filter transmission at the redshifted [O iii] $\lambda 4959$ relative to the filter transmission at [O iii] $\lambda 5007$, with a range between 75\% and 106\%. Three lines, the redshifted $H\alpha$, [N ii] $\lambda 6548$, and [N ii] $\lambda 6584$, contribute to the emission in the 6563/78 filter, with the reddest [N ii] line located at 90\% and 72\% of the peak transmission for NGC 5253 and NGC 5236, respectively. Both the redshifted [S ii] $\lambda 6717$ and [S ii] $\lambda 6731$ are located close to the transmission peak in the 6737/76 filter.

The calibrated $V$ and $R$ images were used to subtract the stellar continuum from the [O iii], $H\alpha + [N\,\text{II}]$, and [S ii] images. After matching the FWHM of the stars in the
broad- and narrowband frames, the continuum images were recursively rescaled and subtracted from the narrowband images until optimal removal of the galaxy stellar continuum was achieved. The field stars were initially used to obtain a first guess on the scaling factor, but refinements on this factor were necessary owing to the bluer stellar continuum of the galaxies’ centers relative to the stars. For the weak [S II] emission we first subtracted the Hα+[N II] nebular emission from the R-band image and then used this nebular emission-free image to remove the stellar continuum from the [S II] image. There is a marked color gradient in the V-band image of NGC 5236 with the center bluer than the external regions; therefore, accurate continuum subtraction over the entire [O III] image of NGC 5236 could not be achieved. We paid particular attention to the central region and obtained a satisfactory [O III] emission-line image of the inner \( \sim 40'' \). This region is comparable in size to the area of H\( \alpha \) emission detected above 5 \( \sigma \) (see \S 3.3 below) and thus is sufficient for our purposes.

The accuracy of the calibration of the narrowband filters was checked against ground-based spectrophotometry of the centers of the galaxies (Storchi-Bergmann, Kinney, & Challis 1995) and, for NGC 5253, against H\( \alpha \) images obtained with the HST WFPC2 (Calzetti et al. 1997). In all cases, our calibrations gave flux values slightly higher than the spectra and the HST image. For NGC 5253, our [S II], H\( \alpha \)+[N II], and [O III] fluxes are about 5%, 7%, and 10% larger, respectively, than what is measured from the spectrum. For NGC 5236, the [S II] and H\( \alpha \)+[N II] image fluxes are 8% and 2% larger, respectively, than the spectrum. To compare our H\( \alpha \)+[N II] image of NGC 5253 with the HST one, the contribution of the [N II] \( \lambda 6584 \) line had to be removed; from the spectrum we estimate that the [N II] flux is on average 13% of the H\( \alpha \) flux, although variations are expected as a function of position (Kobulnicky et al. 1997). After the subtraction of this contribution, our narrowband image gave fluxes consistently \( \sim 6\% \) higher than the HST image. The source of this fairly small, but

\[
\begin{array}{cccc}
\text{FILTER} & \text{Exposure Time}^a & \text{Exposure Time}^b & \text{Exposure Time}^a & \text{Exposure Time}^b \\
\text{NGC 5253} & \text{(s)} & \text{(s)} & \text{(s)} & \text{(s)} \\
\text{NGC 5236} & & & & \\
\text{Harris U} & 900. & 8400. & 210. & 4500. \\
\text{Harris V} & 120. & 1200. & 190. & 920. \\
\text{Harris R} & 240. & 1520. & 260. & \ldots \\
5000/70 & 180. & 10200. & 870. & 3000. \\
6563/78 & 240. & 3900. & 780. & 1440. \\
6737/76 & 12000. & \ldots & 1560. & 3840. \\
\end{array}
\]

\[^a\text{Total exposure times of the final unsaturated image for NGC 5253 and NGC 5236, respectively. Each unsaturated/saturated image is the combination of multiple exposures in the range 30–1200 s.}\]

\[^b\text{Total exposure times of the final images that have the central \( \sim 5''-20'' \) of the galaxies saturated for NGC 5253 and NGC 5236, respectively.}\]
systematic discrepancy is unclear. We have considered undersubtraction of the stellar continuum, filter calibration, and presence of Balmer absorption in the calibration stars, but none of those reproduces all of the observed discrepancy. However, the relative calibration of the three narrow-band images is good at the 5% level. For consistency, we rescale our emission-line images to the spectroscopic/HST values.

For NGC 5253, HST WFPC2 images centered on the Hβ line emission (Calzetti et al. 1997) are used here to supplement the ground-based images. The HST Hβ image has been rotated, smoothed, resampled, and registered to match the ground-based images.

3. ANALYSIS AND RESULTS

3.1. Line Ratio Maps

Ratios of metal-to-hydrogen lines are common diagnostics of the physical conditions of the ionized gas. We produced maps of [S II] λ6717, 6731/Hα and [O III] λ5007/Hβ for NGC 5253 (Figs. 3c, 3e, and 3f), and [S II] λ6717, 6731/Hα and [O III] λ5007/Hβ for NGC 5236 (Figs. 4e and 4f). The line ratio maps have been created using a 5 σ-detection threshold for each line, after all the images have been smoothed to the seeing of the photometrically worst night (~1.2′) and resampled to 5 pixel × 5 pixel bins (1′.3 × 1′.3). The [O III] line maps have been divided by a factor of 1.3 to remove the contribution from the [O III] λ4959. For NGC 5236, we do not have an Hβ emission-line image; thus the corresponding ratio map [O III] λ5007/Hβ could not be constructed. We use the Hα image instead, with cautionary remarks about the potentially large effects of reddening variations in the center of the galaxy (see below). We also note that the difficulty of subtracting the continuum from the [O III] image for this galaxy contributes to the larger uncertainty in the line fluxes; a number of the data bins are below our required 5 σ threshold, and the “usable” [O III] λ5007/Hα map includes the central ~30″ region only. This is slightly, but possibly significantly, smaller than the extent of the 5 σ Hα ionized region, which occupies the central ~40″ (see § 3.3). In NGC 5253, regions beyond the central ~30″ in radius have Hβ flux detections below 5 σ, and we have used the [O III]/Hα ratio instead, assuming that reddening corrections are small at large distances from the center of the starburst (see discussion below).

3.1.1. Underlying Stellar Absorption

Corrections for the stellar absorption underlying the Balmer lines are important especially at the faintest surface brightness levels, where the EW of the emission line is correspondingly small. We used the ratio of the Hα and Hβ emission to the corresponding underlying continua to derive maps of the EW of these lines; for Hα we used the R-band image as continuum, while for Hβ we used the extrapolated continuum image from the HST V and I images of NGC 5253 (Calzetti et al. 1997). The line fluxes were then corrected for the presence of underlying stellar absorption with constant value EW = 3 Å (e.g., McCall, Rybiski, & Shields 1985). Figures 3d and 4d show the Hα EW emission maps of the two galaxies, after the correction. Unknown variations of the underlying stellar absorption EW increase the uncertainty in the line flux at the detection threshold, where the emission-line EWs are generally small (Figs. 3d and 4d). In addition, the contribution of an intermediate/old underlying stellar population proportionally increases as the distance from the center of the starburst (the young population) increases, thus gradually changing the underlying stellar absorption from ~3 Å to ~5 Å. The combination of the two effects implies an uncertainty of ~20% and ~50% for the Hα measurements at the detection threshold in NGC 5253 and NGC 5236, respectively. The variable underlying stellar absorption is taken into account in the following sections every time its effect is relevant to the measurements.

3.1.2. Dust Reddening

Corrections for dust reddening are generally small for the [S II]/Hα and [O III]/Hβ maps, owing to the closeness in wavelength of each pair of lines, but can be large for the [O III]/Hα because the wavelength difference is large. We discuss reddening corrections separately for each of the two galaxies.

Dust extinction in the central ~30′′ × 30′′ of NGC 5253 is highly variable (Calzetti et al. 1997); there is an east-west dust lane bisecting the central section of the galaxy, and the central ionizing stellar cluster is deeply embedded in a highly opaque dust cloud. We thus use the HST reddening map of Calzetti et al. (1997) to remove extinction effects from the line ratios. We assume the reddening is foreground, which should be a reasonable approximation for most regions, since the Hα/Hβ ratio approaches the unreddened case in the vast majority of the bins. However, we already know that the foreground geometry is altogether wrong in the case of the central cluster, where the amount of extinction is above A_V = 10 mag and the geometry is known not to be foreground (e.g., Beck et al. 1996); such cases should be statistically insignificant when trends between lines are analyzed, as they include a relatively small number of bins. Regions beyond ~30′′ radius, where the HST reddening map is not available, are corrected with the assumption of a small, constantly reddening E(B−V) = 0.1, of which 0.05 are from our Galaxy (Burstein & Heiles 1982). This assumption is reasonable, as the Hα/Hβ map indicates that the reddening decreases to small values beyond a radius of ~20′′ from the center (Calzetti et al. 1997).

In the absence of a reddening map for NGC 5236, we have adopted the constant value E(B−V) = 0.35 for the dust extinction correction, which includes both intrinsic and Galactic foreground extinction, as derived from ground-based spectroscopy of the central starburst (Calzetti, Kinney, & Storchi-Bergmann 1994, hereafter CK94). Given the small wavelength difference between [S II] and Hα, the impact of reddening corrections is no larger than 6% for a reddening variation between E(B−V) = 0 to 0.7. The impact is of course much larger for the [O III] λ5007/Hα; the intrinsic ratio changes by 40% if E(B−V) = 0.7 instead of 0.35. We know from the study of Telesco et al. (1993) that there is a considerable amount of dust with a complex geometry in the center of NGC 5236. For this reason, the [O III]/Hα ratio map, which will be briefly discussed in the next sections, should be considered a preliminary substitute for [O III]/Hβ for this galaxy.

3.1.3. The Contribution of [N II] to the Hα Maps

The ratio of the HST/galaxy-based Hα+[N II] images gives an estimate of the [N II] intensity change across the central region of NGC 5253, because the HST image does not contain the [N II] λ6584 emission while the ground-
Fig. 3.—Deepest of our $U$-band images shows the full extent of the central starburst in NGC 5253 (a) after subtraction of the underlying galaxy. North is up, and east is left. Similar morphology and size are observed in the $V$- and $R$-band images. The central few pixels of the $U$ image are saturated and, thus, masked out. The H$\alpha$ image (b) shows that the ionized gas emission extends beyond the region occupied by the massive star population of the starburst. In both (a) and (b) a darker shade means a higher surface brightness. The H$\alpha$ equivalent width (EW) (d) covers the range 10 Å at the edges of the detected ionized region (light gray), to $\sim$ 1000 Å in the center of the starburst (dark gray). The [S II] $\lambda\lambda$6717, 6731/H$\alpha$ is shown in (c), while the [O III] $\lambda\lambda$5007/H$\beta$ and the [O III] $\lambda\lambda$5007/H$\alpha$ line ratio images are in (e) and (f), respectively. The ionization map [O III]/[S II] is shown in (g). In these four panels, a darker shade means a higher value of the line ratio. The last panel (h) shows in black the location of those regions with $\log ([O \text{ III}]/H\beta) > 0.2$ and $\log ([S \text{ II}]/H\alpha) > -0.35$, i.e., areas whose line ratios indicate presence of shocks or other nonphotoionization mechanism. Each image is 2.58 $\times$ 2.58.

Based image does. The image ratio appears constant to within 12% in the central $\sim$ 27$''$ (radius), which is where the signal-to-noise ratio is high. Thus variations of the [N II] intensity are not expected to be more than twice its average value. This is in agreement with results from long-slit spectroscopy (Lehnert & Heckman 1995; Martin 1997), which indicate that the variation in the [N II]/H$\alpha$ ratio is very small for the central $\sim$ 25$''$–30$''$ of NGC 5253 (see, however, Kobulnicky et al. 1997). In the light of this result, we derived a "pure" H$\alpha$ image by removing 17% of the flux from the
The morphology of the nebular gas emission in NGC 5253 has been described by a number of authors (e.g., Marlowe et al. 1995; Martin & Kennicutt 1995; Calzetti et al. 1997). We review here a few basic facts. The ionized gas emission is circularly symmetric around a stellar cluster located almost at the geometric center of the galaxy (Fig. 1, bottom panel); this cluster, with an age of \( \sim 2 \) Myr, is also the youngest stellar cluster in the galaxy (Calzetti et al. 1997). The azimuthally averaged H\( \alpha \) emission monotonically decreases in surface brightness from the cluster outward. The regular morphology of the gas emission is in striking contrast with the morphology of the UV and optical stellar continuum (Figs. 3a and 3b), which is elongated from northeast to southwest, along the major axis of the galaxy (e.g., Martin & Kennicutt 1995). We clearly detect in each of the H\( \alpha \), [O\textsc{iii}], and [S\textsc{ii}] maps the two western bubbles described in Marlowe et al. (1995): the one closer to the minor axis is the weaker of the two, and we detect the outer shell of the expanding gas; the other, which is almost along the major axis of the galaxy, is well detected and shows a wealth of substructure (Figs. 1 and 3). A number of filaments extend outward from the center, both in the north and east-south directions. The presence of ionized gas along the dust lane, southeast of the center, is detected in both our H\( \alpha \) and [O\textsc{iii}] images, with a hint in the 5 \( \sigma \) [S\textsc{ii}] image.

3.2. NGC 5253

3.2.1. The Ionized Gas Morphology

3.2.2. Photoionization and Shock Ionization

Figure 5a shows the line ratios measured in each 1.3-resolution element and compares those with models for gas photoionization and for shock excitation. The photoionization models give the variation of the line ratios for the changing ionization parameter \( U \). One set of models has been taken from Martin (1997), who ran CLOUDY (Ferland 1993) for a range of metallicities and effective temperatures of the ionizing source. Two other models are from J. Sokolowski (1993, private communication), who analyzed the cases of depleted metal abundances and of a hardened photoionizing continuum; the models assume cosmic abundances and an ionizing source given by an instantaneous burst of star formation with a Salpeter stellar-mass function up to 120 \( M_\odot \). The last model represents the scenario in which the soft ionizing photons are the first to be absorbed by the ISM; thus, the ionizing continuum hardens as it travels across the galaxy. Predicted line ratios for shock excitation are from Shull & McKee (1979), for cosmic abundances and a range of shock velocities and for the special case of depleted metal abundances.

The metal-to-hydrogen line ratios change as a function of the ionization parameter and this can potentially explain the observed variation in Figure 5 (e.g., Hunter 1994). The ionization parameter \( U \) measures the amount of ionizing photons relative to the amount of gas. Increasing the distance from the ionizing source decreases the value of \( U \), lowering the [O\textsc{iii}]/H\( \beta \) ratio and increasing the [S\textsc{ii}]/H\( \alpha \) ratio (Domygörgen & Mathis 1994). The data of NGC 5253 appear to follow this trend qualitatively both in Figure 5 and in the ionization map [O\textsc{iii}]/[S\textsc{ii}] of Figure 3g. Except along the dust lane (see discussion below), the [O\textsc{iii}]/[S\textsc{ii}] ratio decreases from the center to the edges of the ionized region. However, a quantitative comparison (Fig. 5a) shows that the [O\textsc{iii}]/H\( \beta \) value decreases less steeply than expected from variations of the ionization parameter, a trend already noted by Martin (1997) for a sample of dwarf galaxies.

The photoionization model with \( T_{\text{eff}} = 50,000 \) K and \([O/H] = 0.2 \) [O/H]_\odot, which closely matches the metallicity of NGC 5253 (about one-sixth [O/H]_\odot), marks a lower envelope to the data points in Figure 5, while it is in reasonable agreement with the data at the highest values of \( U \), in regions closest to the central ionizing source in the star-
burst. A somewhat better representation of the data is given by the model with depleted abundances (J. Sokolowski 1993, private communication), but most of the data points are still above the locus of the photoionization lines. The observed line ratios behave as if there is an increasingly important shock component (Martin 1997) or the radiation spectrum is progressively hardened toward the external regions (Wang 1998).

Ionization in NGC 5253 can be directly compared with the well-studied Large Magellanic Cloud. Figure 5b shows
the \([\text{O} \text{ I}] / \text{H}\beta\) versus \([\text{S} \text{ II}] / \text{H}\alpha\) line ratios of a sample of H\( \text{II}\) regions, giant shells, and supergiant shells in the LMC from Hunter (1994). Although some of the data points show the same extreme behavior as NGC 5253, the majority of the shells agree with photoionization models. The metallicity of the LMC is about twice that of NGC 5253; thus, the comparison between the two galaxies is not immediate, as the LMC data naturally occupy a locus to the lower left relative to the NGC 5253 data. Nevertheless, the majority of the LMC line ratios are between the solar metallicity and the LMC data. The location of the line ratio predictions from shock models is indicated by the filled triangles, giant shells (open circles), and supershells (filled squares).

To discriminate further between ionization mechanisms, we have plotted the ratios \([\text{S} \text{ II}] / \text{H}\alpha\) and \([\text{O} \text{ I}] / \text{H}\beta\) as a function of the physical distance from the central star cluster in NGC 5253 (Fig. 6). The mean value of \([\text{S} \text{ II}] / \text{H}\alpha\) increases (decreases) for increasing distance from the “center of ionization.” Again, photoionization models reproduce qualitatively, but not quantitatively, this trend. The relationship between ionization parameter and distance has been taken from Martin (1997; see her eq. [1]); the size of the ionized sphere has been assumed to correspond to the size of the H\( \alpha\) emission, around 71''–81'' in radius, or 1.4–1.6 kpc. A quantitative test shows that photoionization alone cannot fully explain the observed trend of the line ratios and, in particular, cannot account for the increasing spread about the mean values with increasing distance. The increasing spread with distance is quite evident in the \([\text{O} \text{ I}] / \text{H}\beta\) diagram (Fig. 6b). We interpret this as an effect of the increasing importance of shock ionization (or other nonphotoionization mechanism; see Haffner, Reynolds, & Tufte 1999) over photoionization further from the center. The physical extent of the starburst and metallicity variations may play a role in the line ratio spread, but we do not expect these to be the dominant effects. We will show in the next section that the starburst population extends over much smaller area, less than one-sixth, than the ionized gas. Both the mean value and the spread of \([\text{S} \text{ II}] / \text{H}\alpha\) increase for decreasing H\( \alpha\) surface brightnesses (Fig. 7; see Wang et al. 1998, Martin 1997, and Ferguson et al. 1996a on a variety of galaxies), supporting what is observed in Figure 6. The reddening-corrected ionizing photon rate from the starburst is log \(Q(\text{H}^0) = 52.57–52.78\), depending on the dust opacity adopted for the central star cluster (9 mag \(\leq A_V \leq 35\) mag; Calzetti et al. 1997). These values correspond to a Strömgren radius \(R_3 = 240–280\) pc, for an electron
density of 93 cm$^{-3}$ and temperature $\sim 10,000$ K (Storchi-Bergman et al. 1995; CKS94) and for a filling factor of 0.01 (Martin 1997). The calculated Strömgren radius is at least a factor $\sim 4.5$ smaller than the extent of the H$\alpha$ emission.

3.2.3. The Morphology of “Shocks” and DIG

Adopting arbitrarily the constraints log ([O III]/H$\beta$) $> 0.2$ and log ([S II]/H$\alpha$)) $> -0.35$ to discriminate between predominance of photoionization and predominance of shock excitation/hardening of radiation (or other mechanism), the location of the “shocked” regions is graphically represented in Figure 3h. The figure shows that the purely photoionized region has a circularly symmetric shape centered almost exactly on the main ionizing cluster, with radius $\sim 560$ pc; it is comparable in size to the stellar population of the starburst, although the morphology of the two is different (see next section). The “shocked” gas has a markedly asymmetric morphology; the majority of the bins with log ([O III]/H$\beta$) $> 0.2$ and log ([S II]/H$\alpha$)) $> -0.35$ is located in the southwest region, and there appears to be an overlap of filaments and arches extending out of the main starburst area. The “shocked” gas extends in the direction of the major axis of the galaxy; one would expect expanding gas to prefer the direction of the minor axis (e.g., Heckman et al. 1990; De Young & Heckman 1994; Martin 1998; Meurer, Staveley-Smith, & Killeen 1998), which does not seem to be true for NGC 5253.

The constraint log ([S II]/H$\alpha$)) $> -0.35$ corresponds to a H$\alpha$ surface brightness less than $6.39 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$, or a normalized surface brightness SB(H$\alpha$)/SB$_{e}$ $< 0.01$, in Figure 7. We stress again here that variations in the underlying stellar absorption would have typically no more than a 20% effect on both the SB(H$\alpha$) and the [S II]/H$\alpha$ ratio (see Fig. 3d). The ratio SB(H$\alpha$)/SB$_{e}$ $< 0.01$ marks a sharp increase in the median value of [S II]/H$\alpha$. A similar sharp break is evident also in the histogram of the bins with specific value of H$\alpha$ surface brightness (Fig. 8): below SB(H$\alpha$)/SB$_{e}$ = 0.01, there is a large gradient in the relative number of bins. Such “breaks” have been pointed out by Wang (1998) as the transition between H II regions and DIG. In the case of NGC 5253, the DIG surrounds the
central starburst up to a distance of at least $\sim 1.4$–$1.6$ kpc in some directions (to our detection limit).

3.2.4. The Morphology of the Starburst Population

In order to compare in detail the morphologies of the ionized gas and of the ionizing stars, we have removed the underlying galaxy from the broadband image, so that the structure of the current starburst would be enhanced.

The $U$-band image includes the [O II] $\lambda 3727$ doublet emission in its passband. In the central $15''$, [O II] has $EW = 130$ Å, thus providing about $20\%$ contribution to the $U$ emission. Since we did not observe the [O II] emission, we used the [S II] map, which was rescaled to the [O II] intensity observed by Storchi-Bergmann et al. (1995). This procedure relies on the (reasonable) assumption that [O II] and [S II] have the same morphology and intensity distribution; this is supported by the observations of Martin (1997). The Hz contribution to the $R$-band image has been removed in a more straightforward manner (see § 2). All three broadband images were corrected for the effects of dust reddening using the $HST$ reddening maps [or the constant value $E(B-V) = 0.1$ outside the range of the $HST$ maps] and the prescription of Calzetti et al. (1997).

The $U$-band isophotes external to $\sim 70''$ follow an exponential profile (Caldwell & Phillips 1989) typical of the old stellar populations in spheroidal and irregular dwarf galaxies. Indeed, NGC 5253 would very likely be classified as a dwarf elliptical (Sérsic, Carranza, & Pastoriza 1972) if it were not for the central starburst. At smaller radii there is a clear excess relative to the exponential fit; Caldwell & Phillips attribute this excess to the star formation event that occurred in the galaxy over the last $\approx 1$ Gyr. Not all of this excess is composed of ionizing stars; along the galaxy's major axis, the region between $50''$ and $70''$ is not associated with Hz emission (to our detection limit). The ionizing starburst appears more concentrated than the population excess over the exponential light profile. To remove the nonionizing stellar population underlying the ionizing starburst, we used the isophotes between $50''$ and $70''$, and attempted both an exponential profile and an $r^{1/4}$ law model. The latter fits the nonionizing population isophotes to $r \sim 34''$ better than the exponential profile. This isophotal profile was extrapolated to the center and subtracted from the original image. The residual, namely the central starburst, is shown in Figure 3a for the $U$ band. All three continuum images present the same morphology, thus hinting that dust extinction does not affect the global appearance in the optical passbands. The colors of the underlying galaxy are fairly uniform, with values $U-V = 0.5 \pm 0.2$ and $V-R = 0.80 \pm 0.25$, typical of a stellar population dominated by A7 and later type stars, which will not contribute to the photoionizing luminosity.

The comparison between the starburst continuum emission and any of the line emission or line ratio maps shows an obvious characteristic: the line emission is more extended, by more than a factor of $\sim 2$, than the continuum emission (see Fig. 3a with 3b). This is true for both the photoionized and shock-ionized parts of the nebular line emission, confirming that the photoionized gas is displaced relative to the ionizing stars by more than $\sim 1$ kpc from the external perimeter of the starburst. A plot of the Hz surface brightness as a function of the $U-V$ color of the starburst population shows the expected trend that higher SB(Hz) coincide on average with bluer $U-V$ colors (Fig. 9). The regions with SB(Hz)/SB$e > 0.01$ have typical colors $U-V \approx -0.5$, $-1.3$, corresponding to ages between 1 and 100 Myr for constant star formation and between 1 and 30

![Fig. 8.](image-url) Histogram of the number of bins having a given value of the Hz surface brightness as a function of the surface brightness itself, in NGC 5253. The total area occupied by the bins is normalized to unity. The Hz surface brightness is normalized to the mean half-light radius surface brightness. Values are reported for the surface brightness corrected for the underlying stellar absorption only (crosses) and corrected for both underlying stellar absorption and dust reddening (circles). A "natural" break occurs around $SB(Hz)/SBe = 0.01$.

![Fig. 9.](image-url) Hz surface brightness (normalized to the mean half-light radius surface brightness) as a function of the $U-V$ color of the starburst population, for the same bins as in Fig. 3. The $U$- and $V$-band emission of the underlying $r^{1/4}$ stellar population has been removed. As expected, there is a trend for regions of higher Hz surface brightness to have bluer $U-V$ color. Regions with SB(Hz)/SB$e < 0.01$ correspond to nonionizing or only weekly ionizing stellar populations. The region occupied by the starburst population is only a fraction of the area of the ionized gas emission.
Myr for an instantaneous burst population (Leitherer & Heckman 1995); this agrees with the age range found by Calzetti et al. (1997). A few points in this region have $U - V < -1.6$, bluer than the bluest models for stellar populations. This reflects uncertainties in the color derivation and, possibly, an imperfect subtraction of the strong [O III] emission from the $U$-band image. Lower SBF(Hz) correspond to regions with typical colors of nonionizing or mildly ionizing populations. We highlight again that the ionizing stellar population extends over an area that is less than one-sixth of the area of the detected gas emission.

3.2.5. Star Formation in the Dust Lane

The values of [O III]/Hz along the dust lane (see the little “horn” sticking out at the bottom left-hand corner of Fig. 3f) have median $\pm 6$, compatible with the values in the center of the starburst. In addition, the ratio [O III]/[S II] remains high, around or above 10 (about one-half the value of the central cluster; see Fig. 3g) along the entire dust lane. Insufficient reddening correction due to the presence of the dust lane would make both ratios even higher. This is one of the areas responsible for the marked spread in the [O III]/Hβ values at a large distance from the center. We can place an upper limit [S II]/Hz $< 0.35$ in this area. Both line ratios are compatible with this region being almost purely photoionized. However, there are no obvious ionizing stars in this area, although we cannot exclude that star formation is heavily embedded in the dust lane and thus is not visible. Even if this is the case, star formation in the lane is happening at a relatively low intensity level; the star formation–sensitive 10 μm map of Telesco et al. (1993), indeed, does not show emission along the dust lane, and dust obscuration is less effective at 10 μm than in the optical.

3.3. NGC 5236

3.3.1. Morphology of the Starburst

The global morphology of the ionized gas emission in NGC 5236 is far simpler than in NGC 5253 and, likely, easier to interpret. Most of the Hz+[N II] emission comes from the central ~40°, where the starburst is located, and along the spiral arms (Fig. 2b). Unlike NGC 5253, there is little or no evidence for arcs, loops, or filaments of ionized gas extending outward from the central starburst. In the center of the galaxy, the brightest part of the Hz+[N II] emission, above 15 σ, occupies a region ~30° across (corresponding to a physical size of 540 pc), comparable in size and morphology to the bright-blue stellar emission detected in the $U$ band (above 50 σ; Figs. 4a and 4b). The optically brightest part of the starburst is located in the southwestern arc of blue stellar clumps, about 15° in length. The northern tip of the arc appears to bend in the east direction, but this morphology probably is an effect of the crossing of the dust lane (see Gallais et al. 1991). The arc shape of the stellar continuum is fairly well mirrored by the Hz+[N II] emission, with no obvious exceptions. The ionized gas and blue star morphology of the center of NGC 5236 is typical of the central starbursts hosted in massive galaxies, where rings, arcs, and “spirals” of star formation are common structures (Maoz et al. 1996; Colina et al. 1997). All characteristics of NGC 5236, including those described below, are consistent with star formation occurring in a sharply bounded inner nuclear disk, perhaps defined by the inner Lindblad resonance (ILR) as suggested by Telesco et al. (1993).

Figure 4c displays the HST WFPC1 image of the center of the galaxy in the F336W filter (Heap et al. 1993, roughly corresponding to the $U$ band), where the arc (A in Fig. 4c) clearly splits into several individual stellar clusters and the northern “bend” of the arc (B in Fig. 4c) splits into three clusters. We cannot resolve the individual line emission of each of the clusters in B from the ground-based image, but their summed flux locates the peak of Hz+[N II] emission in the galaxy center, with a total observed flux $F(\text{Hz}+[\text{N II}]) = 1.40 \times 10^{-12}$ ergs s$^{-1}$ cm$^{-2}$, measured in an aperture of 2.6° diameter. The nucleus (N in Fig. 4c) is located about 6° northeast of the arc; it appears as a lump in the ground-based $U$-band image (Fig. 4a), but with a weak Hz+[N II] emission (Fig. 4b).

About 11° northwest of the arc there are two bright H II knots (C and D in Fig. 4c); clump D is not visible in the $U$-band image; they have comparable intensity in the narrow line emission, with the northernmost of the two (D) being only 30% brighter than the other, but very different $U$ brightnesses, with D being 5.9 times fainter than the other. We identify D as coincident with the mid-IR, northern source (Telesco et al. 1993). The difference in line/continuum emission between the two knots is likely an age effect with D being younger than C; if it were simply an effect of dust reddening, D would appear in near-IR imaging, but this is not the case (Gallais et al. 1991). The younger age of knot D is supported by the value of the Hz EW, which is about 180 Å for this knot, while it is only about 90 Å for knot C. Larger values of the EW(Hz) locate comparatively younger regions (Leitherer & Heckman 1995); in the case of the center of NGC 5236, an imaginary line joining region B with knots C and D identifies the youngest part of the starburst, with values EW(Hz) $\sim 200$ Å (Fig. 4d), about twice those of surrounding regions (Telesco et al. 1993). The inferred ages from such EWs are less than 10$^7$ yr for an instantaneous burst of star formation (Leitherer & Heckman 1995; see Puxley et al. 1997).

The three luminous condensations in the arc (A in Fig. 4c, corresponding to multiple clusters in the HST image) are between 1.61 and 2.05 times brighter in $U$ than clump B, while they are a factor between 2.4 and 4.2 fainter in Hz+[N II]. In [O III], the features in arc A are about 2.4 times brighter than B. If the metallicity along the arc is roughly constant, these differences are immediately understandable in terms of dust reddening, with B being more reddened than A. This is reasonable as B is located very close to the north-south dust lane.

3.3.2. Gas Excitation

The [O III] $\lambda 5007$/Hz ratio is plotted as a function of [S II] $\lambda\lambda 6717, 6731$/Hz in Figure 10. Sokolowski’s models, derived for cosmic abundances, are expected to work fairly well for this galaxy, whose center has an average metallicity about twice solar. The data are not inconsistent with photoionization models, in the entire range considered. There is little evidence for shocks in NGC 5236, although our line ratios cannot be used as the only criterion for deciding the ionization mechanism because of the potential for heavy dust reddening effects in the [O III]/Hz ratio. The plot of [S II]/Hz as a function of the distance from the Hz peak (Fig. 11a) also shows that photoionization appears to be the main gas-excitation mechanism, as the trend of the upper envelope to the points closely follows Sokolowski’s model for depleted abundances. Further support to the photoion-
The ionization picture comes from the range of values covered by the [S II]/Hα ratio: it is very close to that measured in NGC 5253, despite the fact that NGC 5236 is at least 1 order of magnitude more metal-rich (cf. Fig. 11a with Fig. 6a). The latter conclusion does not qualitatively change even if there is a 50% uncertainty in the stellar absorption underlying the Hα emission or a similar uncertainty in the [N II] contribution to the Hα image.

The plot of the [O III]/Hα ratio as a function of the distance from the peak of the Hα emission is instead fairly inconclusive (Fig. 11b): here the scatter in the data points dominates any trend. The scatter in Figure 11b is likely the superposition of two effects: one is the inhomogeneity of the dust reddening, which we cannot correct for with our data; the other may be the lack of a correlation between the line ratio and the distance from the peak of the Hα emission. The presence of the second effect is confirmed by Figure 11a. In this case, variations in the reddening induce small changes in the line ratio; nevertheless, the plot still shows a fairly large scatter. The most straightforward interpretation is that the peak of the Hα emission is not the absolute peak of the ionized gas emission. Unlike the case of NGC 5253 (Fig. 6 and discussion in Calzetti et al. 1997), the gas morphology in the center of NGC 5236 cannot be described as the effect of a main central ionizing source but is far more complex with multiple emission peaks of almost comparable intensity (see Fig. 4b).

As in NGC 5253, the largest values of the [S II]/Hα ratio are reached in the regions of lowest Hα surface brightness (Fig. 12). Here, however, the scatter is much larger than in the case of NGC 5253, probably owing to the insufficient extinction correction of the Hα surface brightness and uncertain correction for the underlying stellar absorption. Also, the Hα surface brightness limit reached for NGC 5236 is about 3 times higher than for NGC 5253, owing to shorter exposure times in both the 6563/78 and the R-band filters, only partially compensated for by the fact that the red continuum of NGC 5236 is about 5 times brighter than that of the other galaxy.

The histogram of the number of area bins having a specific value of the Hα surface brightness (Fig. 13) shows that the two galaxies have similar behavior (slope and upper limit) at the high-brightness end but differ quite substantially in the low surface brightness regime. In particular, NGC 5236 does not show the “break” in the power-law trend shown by NGC 5253. Thus, the transition between H II regions and DIG is less clear in the spiral galaxy. Such
the presence of uneven dust/stellar population distribution across the entire galaxy. The direct comparison of the $U$ and Hz images, discussed above (Figs. 4a and 4c), shows that the morphology of the blue stars closely follows that of the ionized gas. This suggests that the $U$-band image of the center of NGC 5236 is tracing the optically detectable starburst population. Figure 14 shows the azimuthally averaged profile of the surface brightness of both Hz and $U$ band in annuli of increasing distance from the center. The two surface brightnesses have similar half-light radii, around 5.5, with profiles of almost identical shape. In both cases the assumption is that the emission of the underlying nonstarburst stellar population is fairly constant out to $\sim 40''$ (see Fig. 14). The almost identical values of the half-light radii also confirm that the gas emission in the center of NGC 5236 is as extended as the starburst population, and there is no evidence for “leakage” of ionized photons beyond the starburst region.

In summary, the characteristics of the nebular emission in the starbursting center of NGC 5236 are typical of gas excited predominantly by photoionization. This conclusion should be regarded as preliminary, for the following three reasons: (1) the continuum-subtracted narrowband images of NGC 5236 are less deep than those of NGC 5253, especially the crucial $[\text{O} \text{ III}]$ image; (2) the contribution of the $[\text{N} \text{ II}]$ lines to the Hz emission is almost 4 times higher in NGC 5236 than in NGC 5253; the impact of variations of the $[\text{N} \text{ II}]/\text{Hz}$ line ratio on the $[\text{S} \text{ II}]/\text{Hz}$ map is moderate if the $[\text{N} \text{ II}]/\text{Hz}$ changes by less than 50% but increases for larger variations; (3) we do not have appropriate information to correct for variations of the dust reddening across the central region. Our $[\text{O} \text{ III}]$ maps of NGC 5236 contain limited information despite the long exposure times (see Fig. 4f). This is a consequence of the large metallicity in this

Variety of behaviors among galaxies has been previously observed (Wang et al. 1998).

The starburst population of NGC 5236 is not easily separated from the underlying stellar population because of

![Fig. 12.](image)

As Fig. 7, for NGC 5236. In this galaxy, the Hz surface brightness within the half-light radius is $3.47 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, which, after correction for a color excess $E(B-V) = 0.35$, becomes $SB_e = 7.69 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. The observed half-light radius Hz surface brightness for this galaxy is a factor of $\sim 1.8$ smaller than in NGC 5253.

![Fig. 13.](image)

As Fig. 8, for NGC 5236 (circles). In this case, the data points are corrected for both underlying stellar absorption and dust reddening. For comparison, the data points for NGC 5253 are also reported from Fig. 8 (triangles). Unlike the case of NGC 5253, no “natural” break in the trend is visible here, except, possibly, for some hint at $SB(\text{Hz})/SB_e \approx 0.15$.

![Fig. 14.](image)

As azimuthally averaged surface brightness profiles of both Hz and $U$-band emission in annuli of increasing distance from peak of emission. Both profiles are normalized to the mean value of an annulus $\sim 7''$ wide at a distance $\sim 30''$ from the emission peak. The similarity of the two profiles is striking, despite the larger obscuring effects of dust in the $U$ band relative to the Hz.
galaxy: higher metallicities correspond to lower intensities for the O$^+\,$ ion emission.

Incidentally, while [S II]/Hα has typical values in the range 0.15–0.4 in the northern spiral arm of the galaxy, the ratio covers the range 0.2–1.4 and has a more extended cross section in the southern spiral arm (Fig. 2c). A difference between the two arms is evident neither from the stellar continuum morphology nor from the colors. Since we cannot easily discriminate between dust reddening and age of the stellar population, a difference between the intrinsic stellar populations in the two arms cannot be excluded.

4. DISCUSSION

The investigation of the morphology and physical conditions of the ionized gas in the galaxy pair NGC 5253/NGC 5236 demonstrates that the ionization structure is different in the two central starbursts and probably reflects the morphological difference of the host galaxies. Both galaxies responded to a possibly common trigger with a large-scale central starburst (size of order 500 pc), but the starburst in NGC 5253 was probably more extended in the past (Caldwell & Phillips 1989). NGC 5236 is also experiencing a somewhat milder event in its center, with a SFR about one-third to one-fourth that of NGC 5253, although dust-reddening corrections are uncertain. The major difference between the two starbursts appears to be, however, in their impact on the surrounding ISM, as discussed below.

4.1. NGC 5253

4.1.1. The Diffuse Ionized Medium

The central concentration of the blue stars relative to the ionized gas seen in NGC 5253 is typical of intense star-forming events, ranging from giant H II regions such as 30 Dor or NGC 604 (Kennicutt & Chu 1994; Muñoz-Tuñón 1994) to blue compact dwarf galaxies (e.g., Meurer et al. 1992). The structure of the starburst in NGC 5253 closely matches these expectations. The extended ionized gas emission is probably the manifestation of the hydrodynamic effects of radiation pressure and stellar winds/supernovae on the ISM surrounding the starburst, in combination with the photoionization effects of luminous sources. This conceptual model accounts for complex structures, such as bubbles and filaments, in the low surface brightness Hα emission. In terms of luminosity, the Hα flux that is not directly associated with massive stars and, thus, can be associated with the DIG is 13% of the total. This fraction is for the projected emission only; we do not attempt to extrapolate it to the entire three-dimensional distribution as this would require “guessing” the gas distribution along the line of sight. The locus of massive stars is defined as the region where the U-band emission from the starburst is detected (Fig. 3a). Thus, about one-tenth, and probably more, of the Hα emission in NGC 5253 is spatially separated from the source of ionization.

4.1.2. The Contribution of Shocks and Other Processes

The peripheral regions of the ionized emission in NGC 5253 show the presence of a shock or other non-photoionization component in the gas-excitation mechanism. Although the candidate shock structures we identify in the previous section (Fig. 3h) need spectroscopic confirmation, it is clear that some contribution to the nebular line emission from nonphotoionization (“shock”) excitation needs to be present to explain the observed line ratios.

The morphology of the “shocked” gas (Fig. 3h) closely follows that of the bubbles southwest of the starburst center and the filaments in the northern region. In particular, the bulk of the “shocked” area is located at the position of the major-axis bubble and extends in the direction of the finger of soft X-ray emission in the map of Martin & Kennicutt (1995) and along the axis of the X-ray emission detected by Strickland & Stevens (1999). The X-ray finger of Martin & Kennicutt extends for about 2′ away from the galaxy center, not very different from the 1.3 scale of the “shocked” region. A possibility therefore exists that the hot gas in overlapping superbubbles, which is most likely responsible for the extended X-ray emission (Strickland & Stevens 1999), also affects the optical emission-line spectrum. Given the relatively low photon luminosity of the X-ray sources in NGC 5253 ($\lesssim 10^{44}$ photons cm$^{-2}$ s$^{-1}$), the X-rays should make a modest contribution to the level of photoionization in most of NGC 5253. However, in addition to shocks within the hot bubbles (see Martin & Kennicutt 1995), there is the possibility that transition layers of warm, rapidly cooling gas exist within or on the boundaries of these regions. This type of emission region includes “turbulent mixing layers,” such as those described by Slavin, Shull, & Begelman (1993), which could become significant sources of emission in regions with low gas column densities. Emission-line ratios from mixing layers can mimic shocks in the diagnostic emission-line ratios that we have available, and this possibility therefore merits future examination. However, since hot ejecta from the central starburst can be responsible for shocking the outer regions of the DIG, we discuss below the viability of shocks to explain the observed line ratios.

A size scale of about 1.3 for the shocked region corresponds to a physical size of 1.45 kpc, which, for an expansion velocity of 35 km s$^{-1}$ (Marlowe et al. 1995), corresponds to an age of 40 Myr for the bubble. Star formation within the central ∼300 pc has been ongoing for ∼100 Myr, long enough to drive such a shock (Calzetti et al. 1997). The low velocity values observed by Marlowe et al. represent a potential difficulty for interpreting the ionization of this region as due to shocks. However, the line-of-sight velocity may not be representative of the expansion velocity of the bubble; if we adopt a shock velocity of 100 km s$^{-1}$, the age of the region decreases to ∼15 Myr.

The Hα intensity associated with the shocked component is 2.2% of the total Hα emission, after correction for underlying stellar absorption and dust obscuration (accounting only the area for which [S II]/Hα is detected above 5σ; see Fig. 3). This value is an upper limit, as the regions we define as “shocked” can also be partially photoionized; we assume, conservatively, that only half, or 1.1%, of the ionized gas emission in the “shocked” areas are actually excited by shocks. This fraction, however, does not include the fainter, more extended DIG, since here [S II] is either undetected or is detected below our 5σ cut. Whichever the actual shocked Hα emission fraction, it will still be a few percent at most. The Hα flux associated with the shock is $3.2 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$, corresponding to a luminosity of $6.1 \times 10^{38}$ erg s$^{-1}$ at the distance of NGC 5253.

We can compare this value with the amount of mechanical energy input expected from the starburst. The reddening-corrected flux density at 2600 Å from the star-forming region is $F(2600) = 4.5 \times 10^{-13}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$, corresponding to a luminosity of $\sim 8.6 \times 10^{38}$ ergs...
s⁻¹ Å⁻¹, from the data of Calzetti et al. (1997). This estimate does not take into account the fraction of massive stars so deeply buried in dust, e.g., along the dust lane, that their accounting is missing from the UV flux; a comparison between the optical nebular emission and the radio thermal emission (Beck et al. 1996) shows that the missing fraction amounts to ≈20% of the reddening-corrected UV flux. Given the star formation history of the galaxy and the above UV flux, the mechanical energy being deposited into the ISM by massive stars is ≈8.5 × 10⁴⁰ ergs s⁻¹ (Leitherer & Heckman 1995), a value very similar to what was calculated by Marlowe et al. (1995) and by Martin & Kennicutt (1995). This energy rate is about 50% higher than the one derived for an expanding superbubble with the age and size given above and density of 12 cm⁻³ (Martin & Kennicutt 1995), using the self-similar solution of Weaver et al. (1977), and is more than sufficient to produce the observed X-ray luminosity (Strickland & Stevens 1999). About 2.5% of the shock input power is emitted in Hα (Binette, Dopita, & Tuohy 1985), implying that the gas shocked by the starburst in NGC 5253 can produce a total luminosity L(Hα) ∼ 2.1 × 10³⁹ ergs s⁻¹.

Most of the detected “shocked” gas component is located in the southwestern quadrant relative to a sphere centered on the main cluster. If the mechanical energy is emitted with bipolar symmetry from the central starburst (Strickland & Stevens 1999), this quadrant is likely to receive ≈25% of the total energy available to shocks, or L(Hα) ∼ 5.3 × 10³⁸ ergs s⁻¹, comparable to the observed luminosity of 6.1 × 10³⁸ ergs s⁻¹. The total mechanical energy available from the starburst can shock excite gas to produce a total Hα luminosity ∼3.4 times what was observed or about one-fourth of the 13% of Hα emission we associate with the DIG. Observationally, photoionization provides between 80% and 90% of the excitation of the DIG in NGC 5253; this fraction is potentially lower, but not lower than ∼70%, even if all the mechanical energy was available to excite the gas.

Notably absent are shocks in the eastern region; in § 3.2.5, we showed that the ionized gas associated with the dust lane in the eastern region is more consistent with photoionization rather than shocks (or other mechanism), even though local stellar ionizing sources have not yet been found. The absence of an obvious shock component here has another interpretation, possibly complementary to the previous one. The dust lane coincides with the position of the extremely weak CO detection in this galaxy (Turner et al. 1997). Turner et al. have interpreted the very low CO luminosity as evidence for the presence of extremely metal-poor gas in the area, possibly infalling gas that is feeding the central starburst. If the metallicity along the dust lane is lower than the average in the starburst, the [O III]/Hβ and [S II]/Hα ratios are expected to be higher and lower, respectively, than the average. Thus, presence of shocks along this region would go undetected by our method, as we are assuming a uniform metallicity for the ionized gas across the entire central region.

4.1.3. The Structure of the Starburst

Shocks in NGC 5253 appear to have a preferential direction along the galaxy’s major axis. In addition the region along the dust lane, namely along the optical minor axis, appears dominated by photoionization. These facts, together with the H I kinematical data of Kobulnicky & Skillman (1995) and the CO detection of Turner et al. (1997), suggest the following picture for the starburst in NGC 5253:

1. The central star formation is being fueled by gas which is either infalling along the minor axis, as suggested by Turner et al., or is located in a “disk” rotating about the major axis, as suggested by Kobulnicky & Skillman on the basis of the H I rotation.

2. Hot ejecta from supernovae explosions and stellar winds drive the expansion of the ISM described in Martin & Kennicutt (1995) and in Strickland & Stevens (1999). The expansion is driven mostly in the direction perpendicular to the disk/infalling gas, where the gas density is lower (or, alternatively, is driven along the gas disk rotation axis). Hot ejecta from the central starburst, thus, shock the gas preferentially along the optical major axis. Also, the shocked gas is detected mainly along the southwestern side of the major axis; the propagation of the northward shocks may be prevented by the high-density region of the infalling gas/rotating gas disk, which is located in the northern side of the star-forming site.

This general picture is rather different from the one found for other dwarf galaxies by Marlowe et al. (1995), where the location of bubbles is preferentially along the optical minor axis, suggesting that the ionized gas expands mainly in the direction perpendicular to the plane of the galaxy. One can speculate that past interaction with NGC 5236 played a role in the geometry of NGC 5253; the massive “companion” is located in the northwest quadrant, at position angle P.A. ∼ −20°. This direction is only ∼25° away from the minor axis and almost orthogonal, just ∼15°−20° away, to the direction of the shocked gas. Thus, the direction along which the encounter between the two galaxies happened may have determined the initial gas-infall and subsequent gas-expansion directions in NGC 5253.

4.2. NGC 5236

For NGC 5236, the gas morphology allows a more straightforward interpretation than in NGC 5253, although our conclusions are limited by the shallowness of the [O III] map and by presence of a large amount of dust in combination with the lack of an Hβ image to perform dust-reddening corrections. The Hα emission correlates fairly well with the blue emission from the ionizing stars, and there is no evidence for extended ionized gas emission. The strong spatial overlap between blue stars and ionized gas indicates that we are not seeing any “bona fide” DIG in the center of this galaxy; rather, ionization appears to be a local process. The [S II]/Hα values fall into the photoionization range even after allowing for large uncertainties in the underlying stellar absorption and in the [N II] contribution, suggesting very little, if any, contribution from a shock or other nonphotoionization component.

The central starburst in NGC 5236 is a milder perturbation on its giant spiral galaxy host than the one in NGC 5253. The past encounter with NGC 5253 may have produced a stellar bar and/or triggered the gas inflow toward the center along the bar. The presence of an inner Lindblad resonance (Telesco et al. 1993) is the additional ingredient needed to produce a ring starburst (Shlosman, Begelman, & Frank 1990). The absence of a shocked component in the ionized gas can be interpreted as an effect of the deep potential well in the center of NGC 5236. The
more massive the galaxy, the harder it is to disrupt the gas disk, especially in a high-density center (De Young & Heckman 1994; MacLow & Ferrara 1998). In NGC 5236, the mechanical energy being deposited into the ISM by the central starburst is \( \approx 2 \times 10^{46} \) erg s\(^{-1}\). This amount of power is probably inadequate to disrupt the ISM in the dense nuclear disk of NGC 5236. The higher gas densities limit the growth of superbubbles, while the larger gravitational forces make expansion outside of the plane more difficult. The calculations of De Young & Heckman refer to disruption along the minor axis, while we are looking at ISM expansion parallel to the gas disk (NGC 5236 is seen nearly face-on). However, if the ISM is left intact along the minor axis, it is even more likely to remain confined in the center of the disk. Lack of obvious filamentary structures, bubbles, and superbubbles in the ionized gas of NGC 5236 fits in this picture.

5. CONCLUSIONS

The analysis of the starburst-galaxy “odd couple” NGC 5253 and NGC 5236 reveals very different ionized gas morphologies. The metal-poor, dwarf member of the pair, NGC 5253, has the DIG emission typical of intense bursts of star formation, that accounts for about 13% of the projected H\(_\alpha\) luminosity. A small (\( \lesssim 10\%\)) but not negligible, fraction of the DIG is ionized by shocks or other nonphotoionization mechanism; this implies that between 80% and 90% of the H\(_\alpha\) emission from the DIG is due to photoionization from massive stars. The morphology of the “shocked” gas is quite peculiar, as it extends along the optical major axis, orthogonal to the direction from which presumably the gas is feeding the central starburst. If the “shocked” gas corresponds to one or more expanding bubbles driven by the central starburst, the in-plane morphology indicates that the metals ejected from the central region will remain inside the galaxy and will not be lost in the intergalactic medium (MacLow & Ferrara 1998). Photoionization of the DIG from massive stars means that about 10% of the ionizing photons are escaping from the central starburst zone.

In the metal-rich, grand-design spiral member of the pair, NGC 5236, there is no clear detection of a DIG component in the starbursting nuclear region, and the ionized gas does not show an obvious shocked component. This is probably because the gas is confined to the center by the deep potential well of the galaxy and remains near the massive stars responsible for its photoionization.

The fraction of DIG to total ionized gas in both starbursts is much smaller, probably owing to projection effects, than the 20%–50% measured in less active star-forming galaxies (Ferguson et al. 1996b; Wang et al. 1997, 1998). Although we can place only a lower limit to the amount of DIG in the two starbursts, it is unlikely that the actual fraction will be higher than what has been observed in other galaxies.

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