

SPATIALLY RESOLVED *SPITZER* SPECTROSCOPY OF THE STARBURST NUCLEUS IN NGC 5253

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ABSTRACT

We present new *Spitzer Space Telescope* data on the nearby, low-metallicity starburst galaxy NGC 5253, from the Infrared Array Camera (IRAC) and the Infrared Spectrograph (IRS). The mid-IR luminosity profile of NGC 5253 is clearly dominated by an unresolved cluster near the center, which outshines the rest of the galaxy at longer wavelengths. We find that the [Ne III]/[Ne II] ratio decreases from ~ 8.5 at the center to ~ 2.5 at a distance of ~ 250 pc. The [S IV]/[S III] follows the [Ne III]/[Ne II] ratio remarkably well, being about 4–5 times lower at all distances. Our spectra reveal for the first time a PAH emission feature at $11.3 \mu\text{m}$, and its equivalent width increases significantly with distance from the center. The good anticorrelation between the PAH strength and the product between hardness and luminosity of the UV radiation field suggests photodestruction of the PAH molecules in the central region. The high-excitation [O IV] $25.91 \mu\text{m}$ line was detected at $0.42 \times 10^{-20} \text{ W cm}^{-2}$. Our results demonstrate the importance of spatially resolved mid-IR spectroscopy.

Subject headings: galaxies: individual (NGC 5253) — galaxies: ISM — galaxies: starburst — infrared: galaxies — ISM: lines and bands

1. INTRODUCTION

NGC 5253 is a nearby, low-metallicity dwarf galaxy with a recent starburst, which is responsible for its infrared luminosity of $L_{\text{IR}} \sim 1.8 \times 10^9 L_{\odot}$ (Beck et al. 1996). Distance estimates vary from 3.3 ± 0.3 Mpc (Gibson et al. 2000) to 4.0 ± 0.3 Mpc (Thim et al. 2003); here we will assume 4.0 Mpc, corresponding to $19.4 \text{ pc arcsec}^{-1}$. With its low metallicity of only about $\frac{1}{6} Z_{\odot}$ (Kobulnicky et al. 1999), NGC 5253 is an excellent target to study starbursts in a low-metallicity environment. The spectral signatures of Wolf-Rayet (W-R) stars suggest a very recent starburst (Beck et al. 1996; Schaerer & de Koter 1997). Cresci et al. (2005) detected 115 star clusters using optical and near-infrared Very Large Telescope images at an age range of 3–19 Myr. Turner et al. (1998) found a compact radio source representing a hidden super star cluster (SSC) in one of the earliest phases of SSC formation ever observed. Its ionizing flux corresponds to several thousand O7 V star equivalents within the central $2''$ (Crowther et al. 1999; Turner & Beck 2004) and an infrared luminosity of $L_{\text{IR}} = 7.8 \times 10^8 L_{\odot}$ (Crowther et al. 1999). Near-infrared observations with the *Hubble Space Telescope* revealed the presence of a double star cluster in the nuclear region, separated by 6–8 pc (Alonso-Herrero et al. 2004). There are indications that an interaction with M83 might have provoked the starburst (Kobulnicky & Skillman 1995).

NGC 5253 has also been studied in the mid-IR with the *Infrared Space Observatory (ISO)* by several authors, for example, Crowther et al. (1999), Thornley et al. (2000), and Verma et al. (2003). With *Spitzer's* increased sensitivity (Werner et al. 2004) and the smaller slit apertures, the IRS (Houck et al. 2004a)⁴ can continue where *ISO* left off. In this Letter, we report on the spatial variations of the physical conditions in the central region of NGC 5253, based on IRAC images and IRS spectral maps.

2. OBSERVATIONS AND DATA REDUCTION

The images were obtained on 2005 January 31 using IRAC (Fazio et al. 2004) at all four bands (3.6, 4.8, 5.8, $8.0 \mu\text{m}$). The observations consist of 12 slightly dithered pointings of 3×12 s exposures each. The data were pipeline-processed by the *Spitzer* Science Center. Longward of $5 \mu\text{m}$, the IRAC images show only one compact cluster and no structure of the host galaxy. To assess what fraction of the total luminosity of the central region is provided by the central cluster, we compare the flux within the central 44 pc (2 pixels) to the total flux within a radius of 330 pc for each channel. The results in Table 1 show the increasing dominance of the starburst nucleus in luminosity with wavelength. We subtracted the IRAC instrumental point-spread functions from the nucleus for all four channels, and the residuals suggest that the central cluster remains unresolved in the IRAC images, which is consistent with its very compact size (Turner & Beck 2004).

The mid-IR spectra were obtained on 2004 July 14, using the high-resolution modules ($R \approx 600$) of the IRS in spectral mapping mode. In the SH (short-high) mode, the map consists of 12 different pointings, overlapping by half a slit width and about one-third slit length, covering an area of $18''.0 \times 23''.6$. In LH (long-high) mode, the map consists of only six different pointings, covering an area of $22''.2 \times 33''.4$. Figure 1 shows the SH and LH slit positions overlaid on the IRAC image of the central region. Both maps are slightly off-center. Additional “sky” measurements, $6'$ from the nucleus, were also taken. The basic processing of the data was performed with version 11.0 of the automated IRS pipeline at the *Spitzer* Science Center. The background was subtracted using the sky images. The spectra were extracted in “full-slit” mode from pre-flat-fielded files using the IRS data reduction and analysis package SMART, version 5.5 (Higdon et al. 2004). The extracted spectra were flux-calibrated with an empirically derived RSRF (relative spectral response function) of α Lac. The spectral overlaps between orders were manually clipped, according to the local signal-to-noise ratio (S/N). Finally, the SH spectra were scaled up by 16% to match the LH continuum fluxes at $19 \mu\text{m}$. This discrepancy in the fluxes is due to the difference between the SH and LH slit sizes.

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3. DISCUSSION

The complete 10–38 μm SH+LH spectrum at the most central position of our map is shown in Figure 2. With a smooth continuum with no significant absorption features, and turnover in the slope around 20 μm , it is dominated by the strong emission lines of [S IV] 10.5 μm , [Ne II] 12.8 μm , [Ne III] 15.5 μm , [S III] 18.7 μm , [S III] 33.5 μm , and [Si II] 34.8 μm . Also detected are the signature of polycyclic aromatic hydrocarbons (PAHs) at 11.3 μm and $\text{H}\alpha$ at 12.37 μm up to a distance of ~ 120 pc. Figure 3 shows eight representative SH spectra at decreasing radial distances, calculated from the central cluster to the center of each slit position. The remaining four spectra of our map are redundant and are not shown, for brevity. The most prominent spectral features are labeled. The line fluxes for each radial position are listed in Table 2.

3.1. Gradients in the Radiation Field

With ionization potentials of 21.56 eV and 40.95 eV for Ne and Ne^+ , respectively, the [Ne III]/[Ne II] ratio is a good measure of the hardness of the radiation field and traces the OB stars. Crowther et al. (1999) measured a relatively low [Ne III]/[Ne II] ratio of 3.5–4.0. However, the larger *ISO* Short Wavelength Spectrometer slit apertures of $14'' \times 20''$ and $14'' \times 27''$, centered on the nucleus, may have also picked up significant line flux at lower excitation from the surrounding galactic population. With the smaller IRS slit aperture of $4.7'' \times 11.3''$, we can probe the influence of spatial resolution on the measured spectral diagnostics. The top panel of Figure 4 shows the [Ne III]/[Ne II] and [S IV]/[S III] ratios as functions of the distance to the central cluster. Both ratios decrease by a factor of 4 over 250 pc, indicating a significant softening of the UV radiation field with distance from the cluster core, and trace each other remarkably well, with the Ne ratio being about 4–5 times higher at all distances. Our high [Ne III]/[Ne II] ratio at the central cluster is comparable to those observed in nearby H II regions such as 30 Doradus and low-metallicity dwarf galaxies such as II Zw 40 (Thornley et al. 2000). Rigby et al. (2004) modeled Ne line ratios for star clusters at low metal-

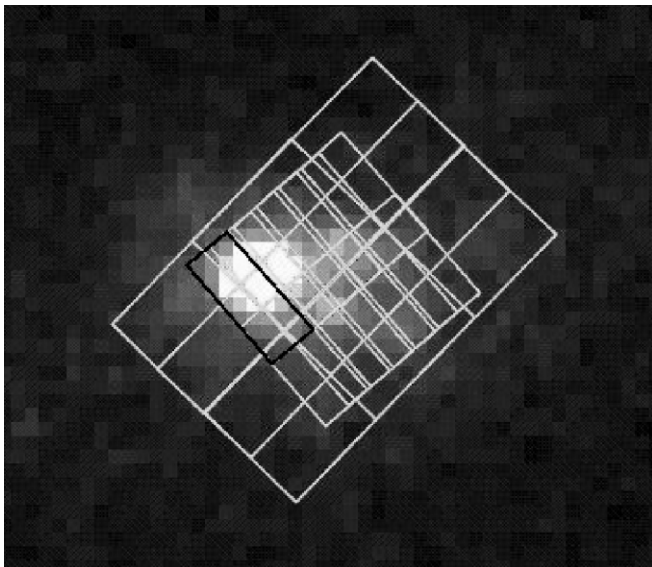


FIG. 1.—Overlay of the SH and LH slits on the IRAC 3.6 μm image of NGC 5253. The image is 1.2×1.0 . Highlighted is the SH slit at the most central position.

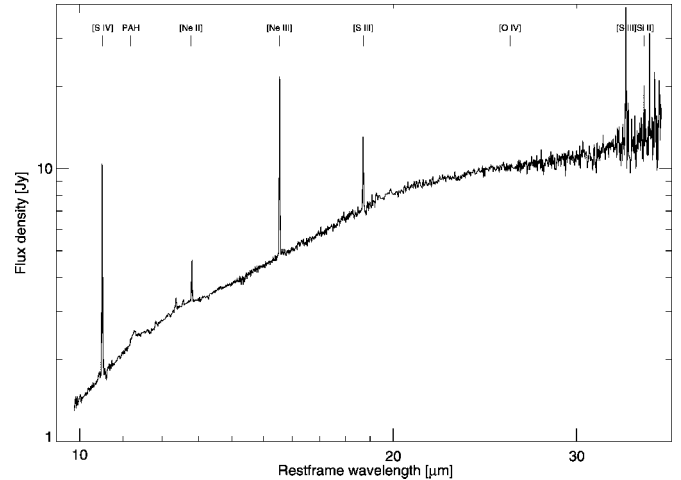


FIG. 2.—Complete IRS SH+LH spectrum of the cluster region of NGC 5253, which corresponds to the highlighted area in Fig. 1. Beyond 35 μm , the spectrum is dominated by noise and detector artifacts.

licity, $Z = 0.2 Z_{\odot}$, and show that a peak ratio of 7.0 is consistent with an upper mass cutoff of $100 M_{\odot}$, at an age of 3–5 Myr.

3.2. Dependence of PAH Strength on the Radiation Field

It has often been asked if PAHs in low-metallicity starbursts appear to be weaker because of low abundance or because they are destroyed by the generally harder radiation fields in these environments (e.g., Wu et al. 2006; Engelbracht et al. 2005; O’Halloran et al. 2006; Houck et al. 2004b; Madden 2000). Our high-S/N spectra clearly reveal, for the first time, the presence of the 11.3 μm PAH feature in all SH positions on NGC 5253, which shows that PAHs can be present in a low-metallicity environment. The middle panel of Figure 4 shows a steady increase of the PAH equivalent width with distance. We assume constant metallicity throughout the galaxy, as no known dwarf has steep metallicity gradients (Kobulnicky 1999). In Figure 4 we investigate the correlation between the measured PAH strength and the “strength” of the UV radiation field, defined by the product of the hardness and the intensity of the radiation field, $([\text{Ne III}]/[\text{Ne II}])([\text{Ne III}] + [\text{Ne II}])$. The bottom panel shows the product between the UV field and the PAH strengths as a function of distance. This product stays almost constant out to a radial distance of 200 pc, meaning that the strength of the UV field and the strength of the PAH emission are strongly anticorrelated. The good anticorrelation over such a large distance (encompassing numerous H II regions) suggests that the photodestruction of PAHs could be the dominant mechanism here. We note that PAH emission models (Li & Draine 2001; Bakes et al. 2001) show that photoionization of hydrogen in PAHs can also cause a decrease in the relative PAH strength above 10 μm . However, we consider

TABLE 1
IRAC FLUX TABLE

λ (μm)	Central Flux (MJy sr^{-1})	Total Flux (MJy sr^{-1})	$F_{44\text{pc}}/F_{600\text{pc}}$
3.6	2616 ± 12	6578 ± 86	0.39
4.5	5069 ± 16	7846 ± 97	0.65
5.8	11640 ± 29	17187 ± 261	0.68
8.0	26869 ± 33	37846 ± 99	0.71

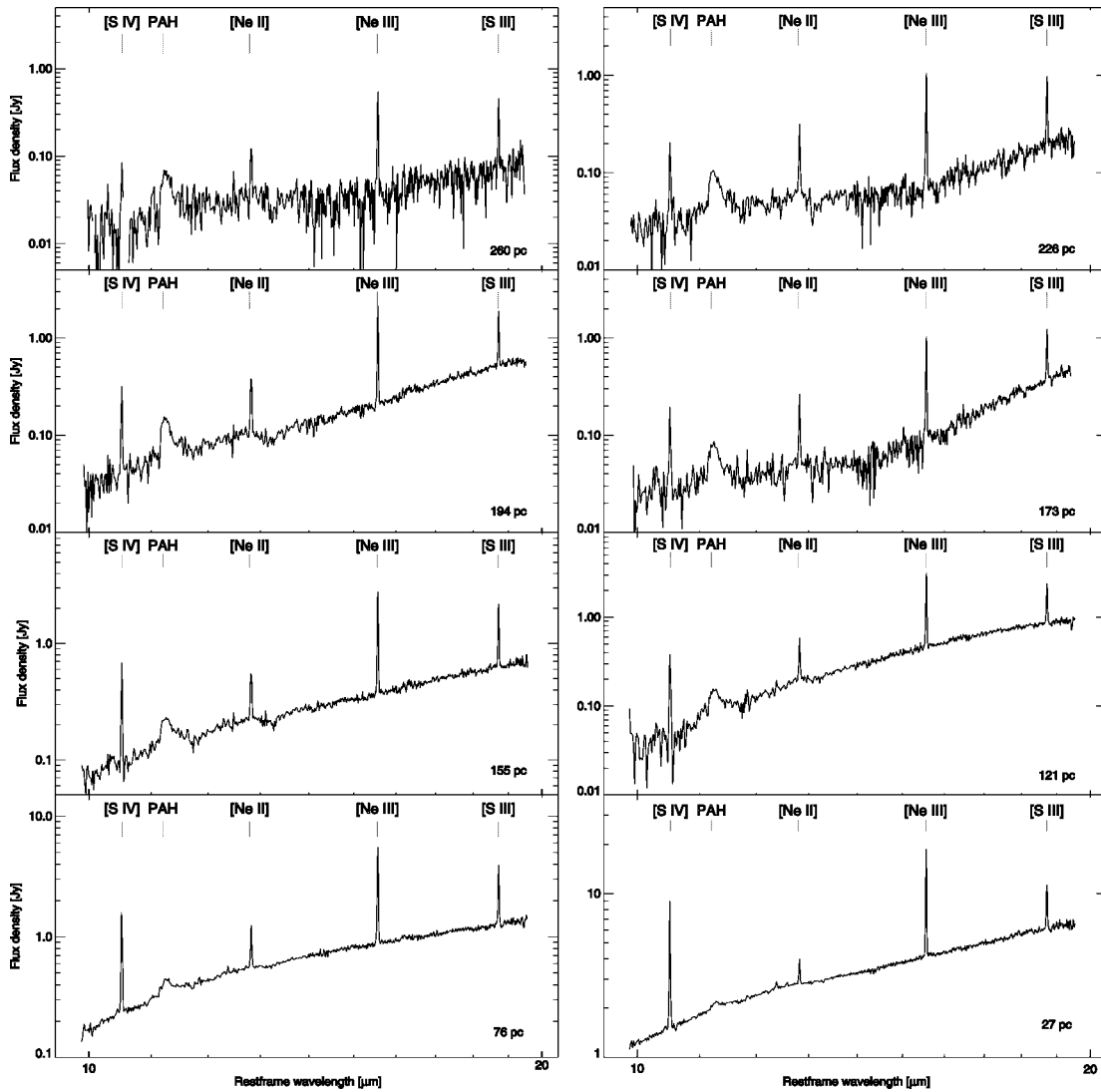


FIG. 3.—IRS SH spectra of NGC 5253 sorted by decreasing distance from the central cluster (*left to right and top to bottom*). The distances are labeled at lower right in each panel.

this effect unlikely, since no ionization effect has been seen in other starburst galaxies (Brandl et al. 2006). For comparison, a low-metallicity system such as SBS 0335–052, where no PAHs have been detected, has an Ne ratio of 4.9 (Houck et al. 2004b), and some of the low-metallicity systems with weak

PAHs studied by O’Halloran et al. (2006) have an Ne ratio of ~ 3 –4. As seen in Figure 4, these ratios correspond to a radial distance inside the PAH destruction zone in NGC 5253. Our results are in good agreement with recent findings by Madden et al. (2006).

TABLE 2
FINE-STRUCTURE LINES AND RATIOS

Distance (pc)	[S IV]		[Ne II]		[Ne III]		[S III]	
	$\lambda_{\text{obs}} = 10.52 \mu\text{m}$ EP = 34.8 eV ($10^{-20} \text{ W cm}^{-2}$)	Hu α $\lambda_{\text{obs}} = 12.37 \mu\text{m}$ ($10^{-20} \text{ W cm}^{-2}$)	$\lambda_{\text{obs}} = 12.83 \mu\text{m}$ EP = 21.6 eV ($10^{-20} \text{ W cm}^{-2}$)	$\lambda_{\text{obs}} = 15.58 \mu\text{m}$ EP = 41.0 eV ($10^{-20} \text{ W cm}^{-2}$)	$\lambda_{\text{obs}} = 18.74 \mu\text{m}$ EP = 23.3 eV ($10^{-20} \text{ W cm}^{-2}$)	[Ne III]/ [Ne II]	[S IV]/ [S III]	
27	37.50 ± 0.21	2.11 ± 0.53	5.63 ± 0.14	47.40 ± 1.21	16.79 ± 0.58	8.41	2.23	
30	33.22 ± 0.84	1.57 ± 0.28	5.90 ± 0.16	40.87 ± 1.90	17.24 ± 0.52	6.93	1.93	
76	8.80 ± 0.21	0.43 ± 0.02	3.51 ± 0.08	16.94 ± 0.50	7.91 ± 0.24	4.83	1.11	
121	2.25 ± 0.32	0.32 ± 0.10	2.02 ± 0.09	8.41 ± 0.31	4.54 ± 0.16	4.17	0.50	
135	7.01 ± 0.45	...	2.62 ± 0.17	12.18 ± 0.33	6.30 ± 0.18	4.65	1.11	
149	6.03 ± 0.51	...	2.75 ± 0.13	11.06 ± 0.25	6.00 ± 0.12	4.02	1.01	
155	3.37 ± 0.24	...	2.58 ± 0.23	8.74 ± 0.14	4.98 ± 0.09	3.39	0.68	
173	1.01 ± 0.08	...	1.09 ± 0.02	3.16 ± 0.11	2.38 ± 0.08	2.91	0.43	
194	1.77 ± 0.04	...	2.17 ± 0.14	6.27 ± 0.09	4.03 ± 0.09	2.89	0.44	
219	0.71 ± 0.01	...	0.60 ± 0.04	1.55 ± 0.06	1.10 ± 0.07	2.60	0.64	
226	1.18 ± 0.18	...	1.36 ± 0.08	3.28 ± 0.11	2.35 ± 0.09	2.42	0.50	
260	0.68 ± 0.12	1.76 ± 0.07	1.12 ± 0.05	2.59	...	

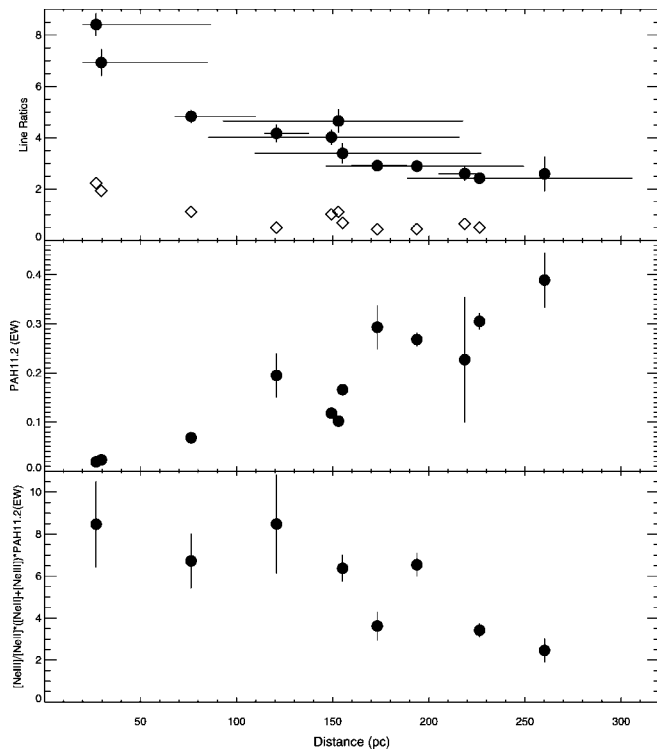


FIG. 4.—*Top*: Variation of $[\text{Ne III}]/[\text{Ne II}]$ (circles) and $[\text{S IV}]/[\text{S III}]$ (diamonds) line ratios with distance to the galaxy's center. Error bars along the x-axis represent the IRS slit length, which translates into a range in radial distance; they are the same for $[\text{S IV}]/[\text{S III}]$ ratios. Error bars along the y-axis represent flux uncertainties. *Middle*: PAH 11.2 μm equivalent widths (EWs) as a function of distance to the nucleus. The error bars represent EW measurement uncertainties. *Bottom*: Dependence of PAH 11.2 μm EW times $([\text{Ne II}] + [\text{Ne III}])/[\text{Ne III}]/[\text{Ne II}]$ with distance (for details, see text). The bars indicate systematic errors.

3.3. $[\text{O IV}]$ Line Emission

With an excitation potential of 54.9 eV, the $[\text{O IV}]$ 25.89 μm line fills the wide energetic gap of mid-IR fine-structure lines between lines that can originate from massive stars and lines that likely require an active galactic nucleus. It has been attributed to various mechanisms, including very hot stars (Schaefer & Stasińska 1999; Morris et al. 2004) and energetic shocks for low-excitation starbursts (Lutz et al. 1998). Our high-S/N spectra reveal a faint $[\text{O IV}]$ line at two slit positions outside the central cluster, with fluxes of about $0.42 \times 10^{-20} \text{ W cm}^{-2}$ at a S/N of 7.1. This is higher than the limit given by Crowther et al. (1999; $0.10 \times 10^{-20} \text{ W}$) but below the upper limit of Verma et al. (2003; $0.9 \times 10^{-20} \text{ W cm}^{-2}$), and in reasonable agreement with the flux measured by Lutz et al. (1998; $0.65 \times 10^{-20} \text{ W cm}^{-2}$). Using the Starburst99 code (Leitherer et al. 1999) assuming an instantaneous burst of star formation with a Salpeter (1955) initial mass function at one-fifth solar metallicity, the observed O IV emission can be produced by roughly 125 W-R stars (WC+WN), consistent with the wide range of O7 V star equivalents (Crowther et al. 1999; Turner & Beck 2004) within the central $1''$ – $2''$. A detailed discussion is given by Martín-Hernández et al. (2005). However, as the $[\text{O IV}]$ emission is only observed in two LH slit positions off the nucleus, it is not obvious that the $[\text{O IV}]$ line is predominantly photoexcited by the central W-R stars. Other excitation mechanisms, such as shocks, need to be considered.

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