SPITZER INFRARED SPECTROGRAPH (IRS)\textsuperscript{1} MAPPING OF THE INNER KILOPARSEC OF NGC 253: SPATIAL DISTRIBUTION OF THE [Ne \textsc{iii}], POLYCYCLIC AROMATIC HYDROCARBON 11.3 MICRON, AND H\textsubscript{2} (0–0) \emph{S}(1) LINES AND A GRADIENT IN THE [Ne \textsc{iii}]/[Ne \textsc{ii}] LINE RATIO

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ABSTRACT

We present our early results of the mapping of the nucleus of the starburst galaxy NGC 253 and its immediate surroundings using the Infrared Spectrograph on board the Spitzer Space Telescope. The map is centered on the nucleus of the galaxy and spans the inner 800 \times 688 pc\textsuperscript{2}. The spatial distribution of the [Ne \textsc{iii}] line at 15.55 \mu m and the polycyclic aromatic hydrocarbon feature at 11.3 \mu m peaks at the center, while the purely rotational transition of molecular hydrogen at 17.03 \mu m is strong over several slit positions. We perform a brief investigation of the implications of these measurements on the properties of the star formation in this region, using theories developed to explain the deficiency of massive stars in starbursts.

Subject headings: galaxies: ISM — galaxies: starburst — infrared: galaxies — ISM: lines and bands — ISM: molecules

1. INTRODUCTION

NGC 253 is a well-studied nearby starburst galaxy located at a distance of 2.5 Mpc (Pence 1980) and is mainly powered by an episode of central star formation. This episode is generally believed to have been caused by material brought to the center of the galaxy by a bar that is clearly visible in the Two Micron All Sky Survey (2MASS) image (Jarrett et al. 2003). The presence of a bar, from both morphological and kinematical evidence, and its role as starburst trigger have been extensively discussed in the literature (Das et al. 2001 and references therein; Scoville et al. 1985; Engelbracht et al. 1998).

Four luminous super star clusters were discovered in the central region by Watson et al. (1996) with the Hubble Space Telescope. They derived a bolometric luminosity for the brightest cluster of $1.3 \times 10^{6} L_{\odot}$, which corresponds to 10\% of the luminosity within a region of a radius of 15\" at the nucleus. In addition, observations of H\alpha emission and earlier \textit{Einstein} and \textit{ROSAT} X-ray data (see Ptak et al. 1997 and references therein) revealed a starburst-driven wind emanating from the nucleus along the minor axis of the galaxy. This wind was well delineated by \textit{Chandra} (Strickland et al. 2000). Engelbracht et al. (1998) studied NGC 253 using near-infrared and mid-infrared lines and concluded that the properties of the initial mass function (IMF) in the starbursting region are similar to those of a Miller-Scalo IMF that has a deficiency in the upper mass cutoff. Their results show that a [Ne \textsc{iii}]/[Ne \textsc{ii}] line ratio of 0.06 is consistent with an upper mass cutoff around 25 $M_{\odot}$. However, they found that for short-lived bursts (1 Myr), the measured neon line ratio is consistent with the formation of massive (50–100 $M_{\odot}$) stars. Verma et al. (2003) also analyzed the SWS fine-structure line, mainly in the context of gas-phase abundances.

In this paper, we present spectral maps of [Ne \textsc{iii}]/[Ne \textsc{ii}] lines, molecular hydrogen lines, and emission from PAHs (Sturm et al. 2000; Rigopoulou et al. 2002; Förster Schreiber et al. 2003; Verma et al. 2003). These authors mainly studied the nuclear region of the galaxy with the Short Wavelength Spectrograph (SWS) and ISOCAM. Rigopoulou et al. (2002) detected several mid-infrared H\textsubscript{2} lines in the SWS spectrum of NGC 253. They derived an H\textsubscript{2} (0–0) \emph{S}(2)/\emph{S}(1) temperature of 380 K with aperture sizes of 14\" × 20\" and 14\" × 27\" for \emph{S}(2) and \emph{S}(1), respectively. Thornley et al. (2000) measured the [Ne \textsc{iii}]/[Ne \textsc{ii}] line ratio using SWS and found a value of 0.06. Since the Ne atom and Ne\textsuperscript{+} ion have an ionization potential of 21.56 and 40.95 eV, respectively, this ratio traces the massive star content, because it is very sensitive to the spectral shape of the UV radiation field.

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In this paper, we present spectral maps of [Ne \textsc{iii}], H\textsubscript{2} (0–0) \emph{S}(1), and the PAH feature at 11.3 \mu m. The sensitivity and small aperture size of the Infrared Spectrograph (IRS) give us the opportunity to do spatial mapping over small scales of the mid-infrared properties of the central region of NGC 253. A total of 45 positions were observed around the bright starburst seen at the center of the galaxy. These observations allowed us to build the map of the [Ne \textsc{iii}]/[Ne \textsc{ii}] line ratio where a spatial gradient is detected. The observations and data reduction are presented in \S 2, and the maps are presented in \S 3.

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The spatial differences in the different maps are briefly discussed in § 4.

2. OBSERVATIONS AND DATA REDUCTION

The observations were carried out during the science verification phase of the IRS on board the Spitzer Space Telescope (Werner et al. 2004), using the Short-High (SH) module (Houck et al. 2004). The high sensitivity and narrow slit sizes of the IRS were used to map the central region of NGC 253. The spectra range from 10 to 20 μm, with a resolution of R ≈ 600. Although the observations of NGC 253 were non-contiguous on the sky, we have produced a “sparsely sampled map” to trace the changes in warm gas and dust properties. The map is centered at a position of R.A. = 00°47′33.2″, decl. = −25°17′19″ (J2000.0), and the step between each pointing position is 15″ along the length of the slit and 9″ along its width.

The map, which consists of 45 different pointings, is centered on the nucleus of the galaxy and spans an area of 70′8 × 60′7 at a position angle of 271°. This corresponds to the central 800 × 688 pc² of the galaxy at the assumed distance of 2.5 Mpc. Each slit covers an area of 1′138 × 5′3 (133 × 60 pc²). The exposure time for each slit position was 88 s.

The basic data reduction was performed by the standard IRS pipeline, version 9.5, at the Spitzer Science Center (SSC). The pipeline removes detector artifacts and cosmic-ray signatures and applies the dark and flat-field corrections (Spitzer Observer’s Manual [SOM]; Spitzer Science Center 2004). Standard full-slit spectral extraction and flux calibration were performed as described in the SOM. The uncertainty in the line fluxes is dominated by the absolute flux calibration. In the present state, these uncertainties are on the order of 30%. Uncertainties on the absolute fluxes have little effect on the uncertainties on the relative fluxes. Line ratios are mostly affected by the determination of the continuum near the emission line. In our data set, this source of error is below 5%.

The 12.8 μm [Ne ii], 15.55 μm [Ne iii], and 17.03 μm H₂ (0–0) S(1) lines are detected with a signal-to-noise ratio (S/N) higher than 3, our detection limit, on all the spectra. Line fluxes were measured by fitting a Gaussian profile after subtracting a second-order baseline fit. Table 1 presents the values of the line fluxes for the central position of the map, which corresponds to the nuclear region of the galaxy. Figure 1 shows the spectrum at the central position and a typical off-center spectrum. The values measured for the central spectrum are shown in Table 1.

The spectral maps are shown in Figures 2–5. The total value of the flux in a given line is shown as the value for the whole slit. In this way, each staring observation becomes a pixel, and the result is a 5 × 9 pixel sparse map. All the images are overlaid on the contours of the 2MASS K-band image.

3. ANALYSIS

The [Ne iii] map (Fig. 2) shows that the peak emission from this line is located at the center of the galaxy. Farther out, the absolute line flux drops quickly. The same behavior is also seen with the PAH 11.3 μm feature (Fig. 3). However, the intensity of the H₂ S(1) line is spatially distributed quite differently. We can see from Figure 4 that the overall intensity of the H₂ (0–0) S(1) line follows the shape of the major axis of the emission seen in the 2MASS image.

Figure 5 shows that the [Ne iii]/[Ne ii] line ratio increases by a factor of 4–6 from the center of the map toward the edges. This increase is higher than our uncertainties on the relative fluxes (see § 2). The line ratio at the central pixel is 0.08, in agreement with what was found with ISO SWS (Verma et al. 2003). The ratio peaks at 0.46 on the southeast edge of the map.

4. DISCUSSION

The [Ne ii] map shows that the strong neon emission is concentrated in the nucleus and decreases sharply outside that region. This behavior is also seen in the [Ne ii] line (not shown here). It is likely that the super star clusters found by Watson et al. (1996) are responsible for the major fraction of the high [Ne iii] flux. The PAH features also follow this trend. These are thought to be excited in star-forming environments, where PAH emission arises predominantly in photodissociation regions at the interface between ionized and molecular gas (Verstraete et al. 1996; Cesarsky et al. 1996; Crêté et al. 1999).

The map of Figure 4 shows a clear correlation between the H₂ (0–0) S(1) line and the major axis of the emission seen in the 2MASS image. This correlation is also seen in the H₂ (0–0) S(2) line (not shown here) and indicates that an excitation source is located along the major axis and raises the H₂ temperature enough to sustain an elevated emission of the 17.03 and 12.27 μm lines. The purely rotational transitions of molecular hydrogen can be triggered by either radiation or shocks.
Fig. 2.—Spectral map of Ne III overlaid on the K-band contours from the 2MASS image. The orientation of this and all subsequent maps is equatorial. The position angle of the major axis in the 2MASS image is 51° (Pence 1981).

Fig. 3.—Spectral map of the PAH feature at 11.3 μm.
Fig. 4.—Spectral map of $\text{H}_2$ (0–0) $S(1)$ over the 2MASS $K$-band contours.

Fig. 5.—Spectral map of the [Ne iii]/[Ne ii] line ratio over the 2MASS $K$-band contours.
(Burton et al. 1992). In dense \((n \geq 10^5 \text{ cm}^{-3})\) photodissociation regions, UV photons from massive stars can produce enough energy to raise the temperature of the \(H_2\) gas so that collisional excitation lines are seen. The molecular gas can also be excited by X-rays (Rigopoulou et al. 2002) or cosmic rays (Bradford et al. 2003). The fact that the \(H_2\) \(S(1)\) line and the PAH 11.3 \(\mu\)m line do not trace each other might indicate that different mechanisms may be at work at the central position and along the major axis.

### 4.2. Spatial Variation of the Ionization Field

The observed increase of the \([\text{Ne} \text{iii}] / [\text{Ne} \text{ii}]\) line ratio (Fig. 5) implies a harder ionization field outside the nuclear region of NGC 253. To first order, this means that the radiation field outside the nucleus is harder than that at the nucleus. In this section, we briefly review the various physical conditions that may lead to an increase of the value of the neon line ratio. We discuss the effect of a metallicity gradient, a modified IMF, and an age gradient on the physical properties of the nuclear region of NGC 253.

Martín-Hernández et al. (2002) showed that decreasing metallicity leads to a hardening of the ionization field, since it affects the line blanketing and the characteristics of the stellar wind. However, a large gradient is needed to account for the observed change. The data of Martín-Hernández et al. (2002) show that in order to triple the neon line ratio, a change in metallicity close to 1 \(Z_\odot\) is required. The maps presented here only cover a radius of 0.5 kpc, so the implied metallicity gradient needed to reproduce the data is on the order of 2 \(Z_\odot\), kpc\(^{-1}\).

Several authors (Puxley et al. 1989; Doyon et al. 1994; Engelbracht et al. 1998; Doherty et al. 1995; Achtermann & Lacy 1995; Beck et al. 1997) have proposed a truncated or steeper IMF to explain the deficiency of massive stars in starburst galaxies. This would imply that the properties of the IMF would change from the nucleus to the outer disk. However, the gradient would imply variations in the IMF only if the stellar populations in the different regions were nearly the same ages.

The analysis of Thornley et al. (2000) showed that aging can cause a softening of the ionization field where a starburst occurs. They pointed out that the observed properties of short-lived starbursts are very sensitive to the massive star content within the first 10 Myr of a star formation episode. This means that the hardness of the radiation field, and thus the \([\text{Ne} \text{iii}] / [\text{Ne} \text{ii}]\) ratio, should decay rapidly if the starburst episode responsible for the ionization field is short-lived. Using this model, our results indicate that the outside regions are, on average, younger than the nuclear region, consistent with star formation propagating outward.

### 5. Conclusions

We present spectral line maps of \([\text{Ne} \text{iii}], H_2 (0−0) S(1)\), and the PAH 11.3 \(\mu\m\) feature, as well as the \([\text{Ne} \text{iii}] / [\text{Ne} \text{ii}]\) ratio and the warm molecular hydrogen temperature of the central region of NGC 253 and its immediate surroundings. The strength of the \(H_2\) lines follows the morphology of the major axis, while the \([\text{Ne} \text{iii}]\) line and the PAH 11.3 \(\mu\m\) feature peak at the location of the nucleus and show no strong correlation with the major axis, suggesting different physical mechanisms in and outside the nuclear region for the PAHs and neon on the one hand and the molecular hydrogen on the other.

A significant gradient in the \([\text{Ne} \text{iii}] / [\text{Ne} \text{ii}]\) ratio is detected. The ratio rises toward the edges of the map, with the lowest value being at the location of the nucleus. To first order, this indicates that the radiation field is harder outside the nucleus, which in turn suggests that there is a relative deficiency of massive stars in the nucleus of the galaxy. With our data set, we were able to briefly explore the variation of the ionization field within a single starburst galaxy and compare it with models that are usually compared with the ionization fields of a sample of starburst galaxies. The spectral mapping capability of the IRS allows detailed studies of the local environment of powerful starbursts and provides unprecedented insight into the star formation process in starbursts. We presented here a small sample of our data set. A more detailed study on the effect of our observations on the determination of the physical properties of the central region of NGC 253 and the stellar population is in preparation.

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