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SWS Spectroscopy of the Starburst Galaxy NGC 3256 ⋆

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Abstract. We present 2.5-40 μm ISO SWS spectra of the starburst galaxy NGC 3256. We have observed many fine-structure lines of various atomic species as well as three rotational transitions of molecular hydrogen. From the [SIII] 18μm/33μm line ratio we infer low electron densities of $\approx$ 300 cm^{-3} in the HII regions. The observed [NeIII]/[NeII] (15μm/12μm), [ArIII]/[ArII] (8.9μm/6.9μm), and [SIV]/[SIII] (10.5μm/18.7μm) line ratios are consistent with an ionizing radiation field with an effective temperature of $\approx$ 41000 K. Comparison of the observed fine-structure line ratios with theoretical models of nebular emission from evolving starbursts shows that stars with masses $\geq$50 M$_\odot$ have been forming recently in NGC 3256. The H_2 observations reveal the presence of warm molecular gas. We estimate that $\approx 10^9$ M$_\odot$ of H_2 gas is present at temperatures close to 150 K. This mass corresponds to a few percent of the total cold molecular mass as estimated from CO studies.

Key words: Galaxies: individual (NGC 3256) – galaxies: interactions– galaxies: starburst– infrared: galaxies

1. Introduction

NGC 3256 is a well known merger exhibiting prominent tidal tails characteristic of an interaction between two spiral galaxies of comparable mass (Toomre & Toomre 1972). Its proximity of 37 Mpc (H_0=75 km s^{-1} Mpc^{-1}), and its total luminosity (8-1000μm) of 3×10^{11} L$_\odot$ (Sargent, Sanders and Phillips 1989), make this merger the most luminous galaxy at redshifts less than 3000 km s^{-1}.

Strong evidence for recent starburst activity comes from the observed strong and extended 10μm emission, half of which originates from outside the central kpc (Graham et al. 1984, Joseph and Wright 1985). That the activity seen in NGC 3256 originates in a starburst is also supported by the prominent PAH emission feature (Moorwood 1986) and the prominent CO absorption band at 2.3 μm detected by Doyon et al. (1994a)

We report on the results from the multi-line spectroscopy on NGC 3256 carried out with the Short Wavelength Spectrometer (SWS) (de Graauw *et al.* 1996, this volume), onboard the Infrared Space Observatory (ISO) (Kessler *et al.* 1996, this volume). Here, we present results of an initial analysis of ionized and molecular gas in NGC 3256 as traced by ionic fine structure lines and rotational H_2 lines detected by the SWS. We also present an analysis of the starburst in NGC 3256 as inferred from the present observations.

2. Data acquisition and reduction

The spectra presented here were taken on 1996, January 16 with the SWS grating spectrometer on board ISO. We carried out observations at the wavelengths of 31 spectral lines between 2.38 and 45 microns. A total of 18 lines were detected. The grating spectrometer covers the region 2.38-45.2 μm with an overall spectral resolution of R $\approx$ 1000-2000 corresponding to a velocity resolution of 300-150 km s^{-1}. The observations reported here were all taken in the standard AOT SWS02 mode, i.e. grating line profiles scan. The aperture sizes ranged between $14''\times20''$ and $20''\times33''$ (see Observer's manual for details). The starburst in NGC 3256 (distance 37 Mpc) is somewhat extended (Graham *et al.* 1984). However, [Ne II] 12.8 μm imaging (Böker 1996) shows the line emission to be strongly peaked, so that we

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will treat NGC 3256 as an unresolved source. The data were reduced using the Interactive Analysis (IA) Package of the SWS team in conjuction with some more sophisticated software tools to improve dark subtraction and flat fielding.

Figure 1 shows selected ionic, atomic and molecular lines observed in NGC 3256. Integrated line fluxes and their corresponding wavelengths as measured from the spectra are listed in Table 1. The intensities were estimated by fitting Gaussian profiles. The uncertainty in the observed fluxes is about 30% due to calibration uncertainties (Schaeidt *et al.*, 1996, this volume).

The extinction towards NGC 3256 is determined from the observed HI recombination lines. Several studies in infrared galaxies have shown that the dust extinction is better described by a mixed dust/gas model rather than a foreground screen model. Assuming the validity of case B for the observed recombination spectrum, an A_V of 35 mags is inferred for the mixed dust/gas model. The spectra were dereddened assuming a $\lambda^{-1.75}$ extinction law for wavelengths $\lambda < 7\mu$m. For wavelengths longer than 7 μm we adopted the extinction law recommended by Draine (1989).

Table 1. *Fluxes of emission lines*

Identification	λ μm	Observed $\times 10^{-20}$Wcm^{-2}	Dereddened $\times 10^{-20}$Wcm^{-2}
H_2(1-0Q(3))	2.429	0.38	6.55
HI (Br$_\beta$)	2.650	3.83	44.2
HI (Br$_\alpha$)	4.320	4.3	13.5
Fe II	5.39	2.57	5.2
Mg V	(5.66)[a]	<0.59[b]	
H_2 S(5)	6.97	4.70	7.37
Ar II	7.05	17.2	26.7
HI (Pf$_\alpha$)	7.53	2.07	6.07
Ar III	9.07	2.80	16.37
Ne VI	(7.71)	<1.27	
SIV	10.60	0.86	5.37
H_2 S(2)	12.39	2.35	5.35
Ne II	12.93	79.5	160.
NeV	(14.45)	<1.08	–
NeIII	15.70	15.9	27.55
H_2 S(1)	17.19	11.5	23.75
FeII	18.09	<0.81	–
SIII	18.89	28.4	112.2
ArIII	(22.04)	<0.31	–
FeIII	23.14	2.32	3.61
FeI	(24.26)	<0.64	–
NeV	(24.53)	<0.63	–
SI	(25.47)	<0.93	–
OIV	(26.14)	<0.28	–
FeII	26.23	3.38	5.1
H_2S(0)	(28.50)	<3.9	–
SIII	33.79	83.8	145.0
SiII	35.14	140.0	227.0
FeII	(35.66)	<1.19	–
NeIII	(36.33)	<2.86	–
H_2O	(40.70)	<0.77	–

[a]:Expected wavelength
[b]:Upper limit at 3σ level

3. Results

We probe the physical properties of the ionized emitting regions based on the fine structure lines observed. The ratio of lines with different critical densities from ions of similar ionization potential is sensitive to the density in the range between the critical densities, similarly the ratio of lines with similar critical densities but from ions of different ionization potential is sensitive to the ionization parameter in the range of ionization between the ionization potentials of the species considered.

3.1. Electron Density

The electron density of the ionized gas may be inferred using the observed ratio of the [SIII] 18 and 33 μm lines. This ratio is sensitive to changes in the electron density for the $100 \leq n_e \leq 10^4$ cm^{-3} region, but quite insensitive to changes in temperature for the region 5000 to 10000 K (see i.e. Mendoza 1983). The dereddened [SIII] line flux ratio yields then an electron density $\approx$ 300-400 cm^{-3}.

The current results are in agreement with the upper limit of $\eta_e \approx 1400$ cm^{-3} reported from Carral et al. (1994) based on their measurements of the [OIII] (88μm/52μm) line ratio.

3.2. The radiation temperature and starburst in NGC 3256

We have used the photoionization codes CLOUDY version C84 (Ferland 1991), and ION (Netzer *et al.*, 1993) to determine the effective temperature of the ionization radiation field in NGC 3256. The assumption that the typical source size is comparable to the the overall size of the starburst, together with the electron density derived from the [SIII] lines and the typical Lyman continuum luminosity, lead to an ionization parameter log(U)$\approx$-2.5. The element abundances were solar. We investigated the effect of the various stellar atmosphere models by using the models of both Kurucz (1992) and Sellmaier *et al.* (1996).

Based on the fine-structure line ratios of [NeIII]/[NeII] (15μm/12μm), [ArIII]/[ArII] (8.9μm/6.9μm), and [SIV]/[SIII] (10.5μm/18.7μm) and the Kurucz and Sellmaier models we have found that the best-fitting effective temperature T_{eff} is approximately 41000$\pm$3000 K, with the error estimate reflecting the differences of the adopted model atmospheres. Effective temperatures of the order

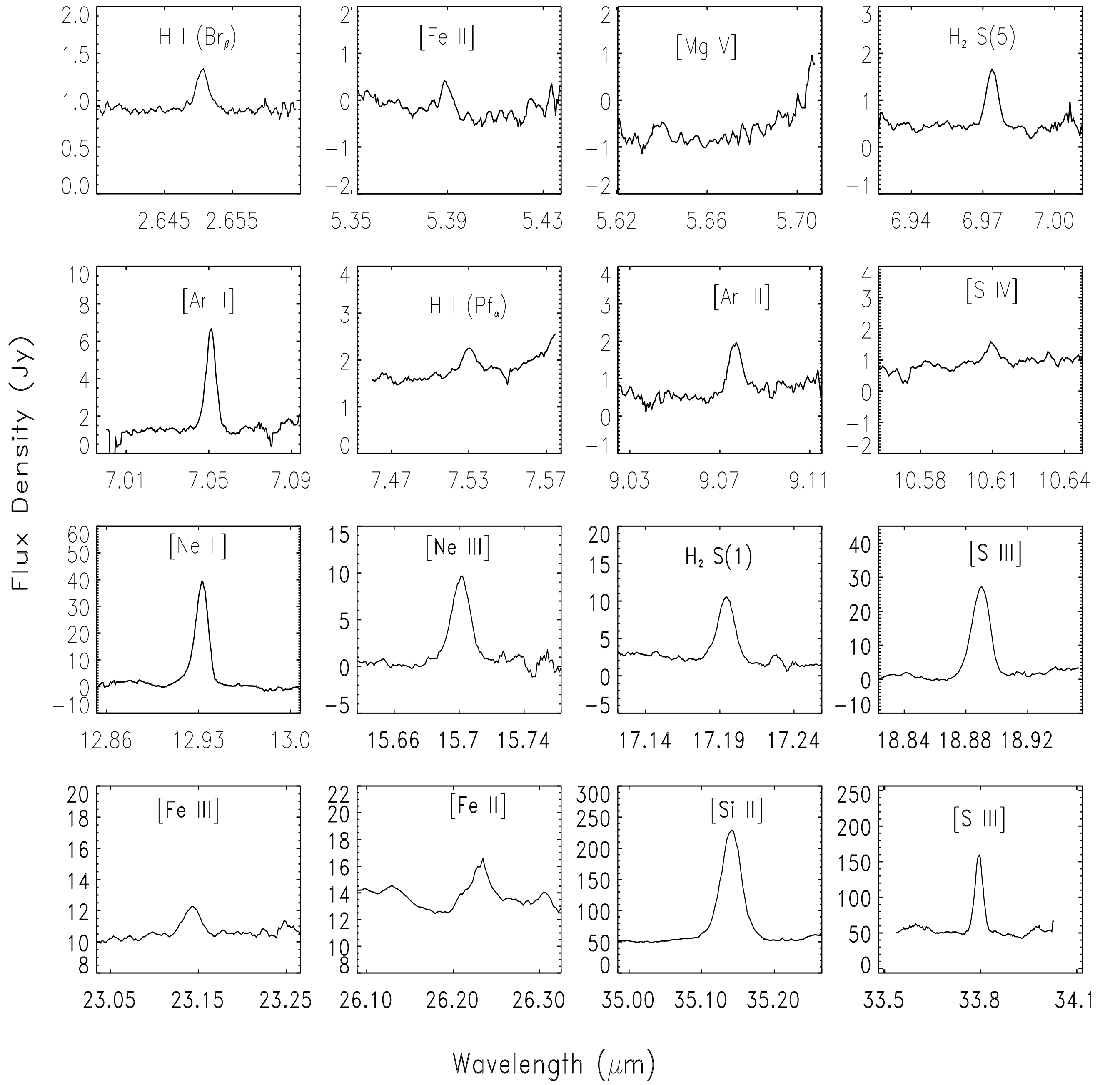

Fig. 1. ISO-SWS line spectra for NGC 3256

of 41000 K correspond to a stellar type of O5-O6 with a mass of 40 $M_\odot$. In the simplified case of a ZAMS cluster with a Salpeter Initial mass Function (IMF) with a slope of -2.4, the effective temperature of 41000 K corresponds to an upper mass cutoff of ≈ 45 $M_\odot$, which as pointed out by Kunze *et al.* (1996, this volume) can be considered as a lower limit to the actual upper mass cutoff in the more realistic case of an evolving starburst.

Using the evolving star cluster model of Kovo and Sternberg (1996) (see Lutz *et al.*,1996, this volume) we find that the starburst event in NGC 3256 is best fit by an extended burst of age and duration of 1 to 2×10^7 years and upper mass cutoff in the range from 70 to 100 $M_\odot$.

The inferred upper mass cutoff of ≥ 50 $M_\odot$ is significantly larger than previous estimates of $\approx$30 $M_\odot$ such as those presented by Doyon et al. (1994) which were based on the near-IR HeI/Brγ diagnostic ratio which is difficult to interpret (Shields 1993). Our data show that *formation of very massive stars is probably not inhibited in NGC 3256.*

Our present method of using ISO mid- and far-infrared fine structure line ratios provides a more robust diagnostic of the effective temperature of the ionizing stars T_{eff}, and consequently upper mass cutoffs. The method has the advantage of these lines being sensitive only to density variations and insensitive to the details of HII region geometry (as in the case of the HeI/Br$_\gamma$ ratio). Moreover, these lines although still suffering from extinction prove to be better tools for probing the obscured regions of galactic nuclei.

3.3. Molecular Hydrogen Mass

Molecular hydrogen, one of the major constituents of the interstellar medium, has up to now been observed in external galaxies in near-infrared vibrational transitions. ISO offers the unique opportunity to observe H_2 in pure rotational emission lines. We have used the SWS to detect, for the first time, pure rotational H_2 emission in several galaxies, e.g. NGC 6240, NGC 4945, Arp 220. In NGC 3256 we detected the S(5) 6.91 μm, S(2) 12.28 μm, and S(1) 17.04 μm lines.

In Figure 2 the derived H_2 column densities (cm^{-2}) in the J=3, 4, and 7 levels divided by the level statistical weights are plotted against upper level energies (in K). Assuming thermal emission, it is apparent that H_2 in a range of gas excitation temperatures is present in NGC 3256. To estimate the temperature of the "warm" gas component a line is fit through the S(1) and S(2) points, whose inverse slope is proportional to temperature. The temperature of the warm gas is estimated to be $\approx$ 240 K. The origin of the warm H_2 gas is uncertain, it may be produced in shocked or UV heated clouds associated with the on-going star formation. The same conclusion was reached by Doyon *et al.* (1994b) in their studies of H_2 in NGC 3256. The S(5) line is significantly stronger than expected from thermal emission from $\approx$ 240 K gas, suggesting that it arises in warmer gas or is excited in a different way.

From our observed upper limit of 3.9$\times$ 10^{-21} W cm^{-2} in the S(0) line, which corresponds to a J=2 column density of less than 2.6$\times$10^{20} cm^{-2}, it follows (see Fig. 2) that the gas emitting the S(1) line must be at a temperature of at least 140 K. This value is comparable to the temperature of the S(1) emitting gas in other galactic (Wright priv. comm.) or extragalactic ISO sources (Valentijn, *et al.* 1996, this volume). Assuming a gas temperature equal to 150 K, our measured column density of 3$\times$ 10^{19} cm^{-3} in the J=3 level corresponds to a (warm) molecular mass of $\sim$10^9 M$_\odot$. This mass is a few percent of the total (cold) molecular mass of 3$\times$10^{10} M$_\odot$ inferred from CO 1-0 emission from the central region of NGC 3256 (Aalto et al. 1991). We note that our finding that $\approx$ 3% of the molecular gas may be at temperatures of $\sim$150 K is consistent with the conclusions of Stacey et al. (1991) who found that typically a few percent of the H_2 mass is in warm molecular clouds heated by stellar radiation fields. This suggests that much of the H_2 emission we have observed may be produced in photon-dominated regions (PDRs).

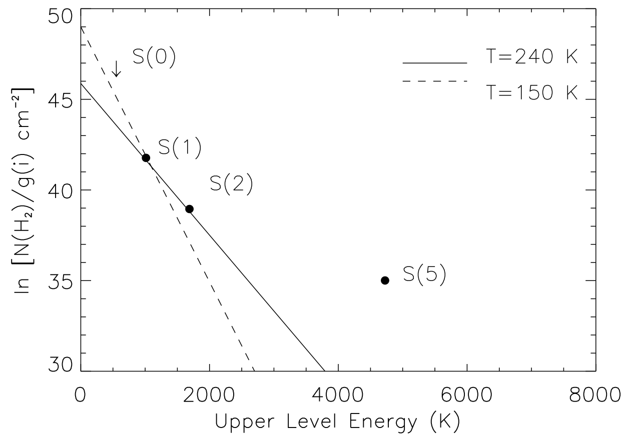

Fig. 2. A plot of column density against energy level for the excited levels of H_2. The straight line is the 236 K fit to the S(1) and S(2) lines while the broken line corresponds to a 150 K temperature consistent with the S(0) upper limit.

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References

Aalto,S., Booth,R.S., Black,J.H., et al., 1991, A&A 300, 369
Böker, T., 1996, PhD Thesis, Ludwig-Maximilians Univ., München
Carral,P., Hollenbach,D.J., Lord,S.D., et al., 1994, ApJ 423,223
de Graauw, Th., Haser, L., Bauer, O., et al., 1996, A&A, this issue
Doyon,R., Joseph,R.D., and Wright,G.S.,1994a, ApJ 421,101
Doyon,R., Joseph,R.D., and Wright,G.S.,1994b, ApJ 421,115
Draine,B.T., 1989, in Proc. 22nd ESLAB Symp. on IR Spectroscopy in Astronomy, ed. B.H. Kaldeich, ESA SP-290,93
Ferland,G.,1991,Univ. of Kentucky, Ast. Dept. Int. Report
Graham,J.R., Wright,G.S, Meikle,W.P.S., et al. 1984, Nat 310,2313
Joseph,R.D., and Wright,G.S., 1985, MNRAS 214,87
Kessler, M.F., et al., 1996, A&A, this issue
Kovo, O., and Sternberg, A., 1996, in prep.
Kunze, D., Rigopoulou, D. Lutz, D., et al., 1996, A&A, this issue
Kurucz, R.L., 1992, Rev. Mex. Astron. Astrofis., 23,181
Lutz, D., Genzel, R., Sternberg, A., et al., 1996, A&A this issue.
Mendoza, C., 1983, in IAU Symp.103, Planetary Nebulae, ed. D.R. Flower (Dordrecht:Reidel), p. 143.
Moorwood,A.F.M., 1986, A&A 166,4
Moorwood,A.F.M., and Oliva,E., 1994, ApJ 429,602
Netzer, H., 1993, ApJ 411,594
Sargent,A.I., Sanders,D.B., and Phillips,T.G., 1989, ApJ 346,L9
Schaeidt, S., et al., 1996, A&A, this issue.
Sellmaier, F.H., Yamamoto, T., Pauldrach, A.W.A., Rubin, R.H.,1996, A&A 305,L37
Shields, J.C., 1993, ApJ 419,181

Stacey,G.J., Geis, J.B., Genzel, et al. 1991, Ap.J., 373, 423
Toomre,A., and Toomre,J., 1972, ApJ 178,623
Valentijn, E.A, et al., 1996, this issue

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