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The SWS survey for rotational H_2 lines in late-type galaxies *

Observations of the central regions of NGC 6946

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Abstract. We report the first extragalactic detection of the pure rotational H_2 S(0) and S(1) lines at 28.2 and 17.0 μm in the central 130 pc molecular complex of the nearby Scd galaxy NGC 6946. We deduce a temperature of this gas component of 170 K and a mass of $5 \cdot 10^6\,M_\odot$ for an ortho/para ratio of 3, corresponding to the ratio of statistical weights. The warm gas is confined to a $\sim 5''$ (135 pc) diameter region where a moderate nuclear starburst accounts for the elevated temperature. Depending on the assumed CO/H_2 conversion factor, the warm component contains of the order of 5–10% (with formal lower and upper limits of 2 and 20%) of the total molecular mass in this region. CO data had indicated the presence of this warm gas, but did not provide a mass measurement. The ISO results can fully account for the warm component indicated by the CO data. The CO/H_2 conversion factor for the ^{12}CO $J = 1 \rightarrow 0$ line is not strongly affected by the presence of the warm component.

Key words: Galaxies: individual: NGC 6946; Galaxies: ISM

1. Introduction

Using the Short Wavelength Spectrometer (SWS; De Graauw et al. 1996) on board the Infrared Space Observatory (ISO; Kessler et al. 1996) we are conducting a survey for molecular hydrogen emission in the central regions and disks of spiral galaxies of *normal and intermediate* infrared luminosity. Outside the Galaxy, H_2 emission has so far only been detected in the rovibrational lines near 2.1 μm, from the centres of about 50 starburst, active, and *(ultra)luminous* infrared galaxies. In nearby objects these lines trace typically only $10^4\,M_\odot$ of H_2, heated to a temperature of $\sim$ 2000 K by intense star formation, an active nucleus, or shocks, and even for the most luminous objects such as NGC 6240 (Van der Werf et al. 1993), only a fraction of 10^{-6} or less of the total amount of H_2 is sampled by the rovibrational lines.

At lower temperatures, the rovibrational lines are too faint and most of our knowledge about the H_2 content of spiral galaxies comes from observations of CO, assuming a CO/H_2 conversion factor derived for Galactic giant molecular clouds (Sanders et al. 1985). In this way, total H_2 masses in intermediate infrared luminosity galaxies were estimated in the range $10^9 - 10^{10}\,M_\odot$ (Tinney et al. 1990), with corresponding surface densities of $\sim\,10\,M_\odot\,pc^{-2}$ in the disks to $\sim\,10^3\,M_\odot\,pc^{-2}$ in the centres. High H_2 surface densities throughout galactic disks of $\sim\,100\,M_\odot\,pc^{-2}$ have been suggested based on, for instance, opacity studies (Valentijn 1990) and Galactic CO absorption data (Lequeux et al. 1993).

ISO's SWS provides a unique possibility to observe moderately warm H_2 directly in the pure rotational emission lines. Since the H_2 molecule is homonuclear with no permanent dipole moment, transitions with $\Delta J = \pm 1$ are strictly forbidden, and the rotational ladder consists of an ortho (J odd) and a para (J even) series of weak quadrupole transitions. The ortho/para ratio will be three if set by the ratio of statistical weights. In Table 1 we list the lowest purely rotational transitions together with the estimated SWS detection limits expressed as a lower limit on the temperature of the gas for a given gas mass within the SWS aperture (at a distance of 5 Mpc) and for a given mass surface density averaged over the aperture (distance independent). The spectral resolution of the SWS for these lines is in the range 130–330 km s^{-1}, which is well matched to typical velocity dispersions in galaxies. Thus the SWS is well suited for a survey of H_2 emission in those galaxies where surface densities in excess of $50 - 100\,M_\odot\,pc^{-2}$ with gas temperatures above $\sim 60 - 80$ K are present.

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Table 1. Preliminary sensitivity (4σ) and temperature limits for the indicated masses (at distance 5 Mpc) within the ISO aperture and aperture-averaged surface densities

λ [μm]	line	time [sec]	4σ [W m^{-2}]	$3 \cdot 10^8$ M$_\odot$ [K]	350 M$_\odot$ pc^{-2} [K]
28.2188	S(0)	1000	$2 \cdot 10^{-17}$	> 71	> 63
17.0348	S(1)	300	$5 \cdot 10^{-17}$	> 75	> 74
12.2786	S(2)	300	$10 \cdot 10^{-17}$	> 94	> 93

We are conducting such a survey for a sample of normal and intermediate infrared luminosity galaxies, selected mainly for high gas content and proximity. Here we report the results of one of the first of our observations, targeted at the centre of the nearby Scd galaxy NGC 6946 ($L_{\rm IR} \approx 8 \cdot 10^9$ L$_\odot$, Engargiola 1991), which (together with NGC 891 and NGC 3079) is part of our intermediate luminosity sample. For the uncertain distance to NGC 6946 we adopt a value of 5.5 Mpc (Tully 1988), which leads to an exponential scalelength of the disk of 3.4 kpc, close to the average value of normal spiral galaxies.

2. Observations and data reduction

The nuclear region of NGC 6946 was observed with the long wavelength grating section of the SWS using AOT2 at the wavelengths of H_2 S(0), S(1) and S(2). Details of the observations are given in Table 2. The data have been wavelength calibrated as outlined in Valentijn et al. (1996). For a description of the flux calibration we refer to Schaidt et al. (1996). All lines were observed with the same detector, the BIBIB Si:As array. The uncertainties in the spectra are strongly affected by drifts in the dark current and detector responsivity, which are believed to be caused by cosmic ray hits on the detectors and the amplifier sections. The present results use the best available techniques to model these drifts.

Figures 1, 2 and 3 show the resulting spectra, and the measured line fluxes are listed in Table 2. The S(1) line is clearly detected, with an observed linewidth, expressed as $R = \lambda/\delta\lambda$, of 1635 ($\Delta v$ = 180 km s^{-1} FWHM). This linewidth matches that expected for an unresolved line of an extended source filling the aperture (R = 1514, calibrated to $\sim$ 2% accuracy, Valentijn et al. 1996). However, CO observations of NGC 6946 (Ishizuki et al. 1990) indicate that a velocity range (due to rotation) of about 160 km s^{-1} is present within the aperture, which would, for a source filling the aperture, result in R = 1177. The higher R value observed can only be obtained if the source is much smaller than the aperture, giving a higher instrumental resolution (cf., Table 2). The theoretical linewidth for a point source with zero velocity range is R = 2232 (Δv = 130 km s^{-1}) at this wavelength. Due to the large velocity gradient in the nuclear gas (Ishizuki et al. 1990), a small extended source will contain a sufficiently large velocity range to reproduce the observed linewidth. The best match between observed linewidth, theoretical resolution and gas kinematics is found when the H_2 emitting region has an angular diameter of $5 \pm 1''$ (135 pc) and a velocity range of 110 ± 10 km s^{-1}. For the computation of line fluxes (Table 2), which involves an estimate of diffraction losses (which depends on the angular size of the emission), we adopt these values.

Table 2. SWS AOT2 observations of NGC 6946

	12 μm - S(2)	17 μm - S(1)	28 μm - S(0)
Instrumental parameters			
Revolution	72	56	98
PA slit [deg]	106	90	72
R point	1592	2232	1504
R extended	1032	1514	904
Aperture [$'' \times ''$]	14×27	14×27	20×27
Observational results			
Line flux [Jy]	< 0.45	2.03	0.3
σ of detection	$2-3$	14	5
Continuum flux [Jy]	0.9	1.53	2
Line width (R)	-	1635	-
Intensity [W m^{-2}] [a]	$< 0.93 \cdot 10^{-16}$	$2.73 \cdot 10^{-16}$	$0.41 \cdot 10^{-16}$

[a] For a 5$''$ source with 110 km s^{-1} velocity range

The two para lines S(0) and S(2) are significantly fainter than the ortho line S(1). Close to the expected wavelength of the S(2) line (Fig. 2) we detect a faint signal, which is however suspect since the relative spectral response function (RSRF) of the array shows fringes which are in phase for the various detector elements at the redshifted wavelength of S(2). We thus prefer to label this signal as an upper limit. At the expected wavelength of S(0) we do detect a faint but significant signal, which is resistent to the effects of the RSRF (Fig. 3), and therefore a secure detection of the H_2 28 μm S(0) line.

3. Molecular hydrogen gas temperature and mass

The detections of S(1) and S(0) and the upper limit on S(2) imply line ratios S(1)/S(0) = 6.7 and S(2)/S(1) $<$ 0.34. Since all data have been obtained with detectors of the same type, a number of systematic effects tend to cancel in the line ratios, which are therefore believed to be more accurate than the separate line fluxes. For $n_{\rm H_2} > 10^4$ cm^{-3} (as supported by CO data, *e.g.* Wall et al. 1993) the rotational levels involved are thermalized and the line ratios can be used to derive gas temperatures of 170$\pm$10 K and $<$ 330 K for an ortho/para ratio of 3, and 290$\pm$30 K and $<$ 200 K for an ortho/para ratio of 1. Due to the steep dependence of line ratios on temperature in this temperature regime, the relative accuracy of the derived temperatures is higher than that of the line ratios. For an ortho/para ratio of 1 the derived temperatures are internally inconsistent and multiple temperature components are required to fit the data. However, since the analysis in the following section shows that only one warm gas component is required by the CO data, we

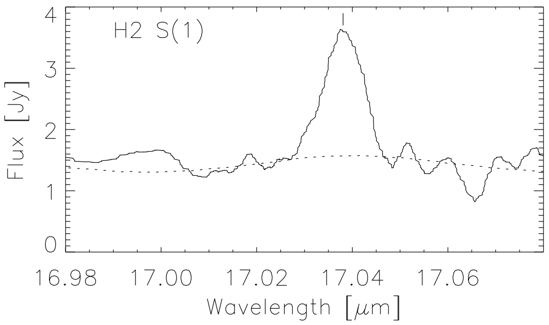

Fig. 1. ISO-SWS spectrum of the H_2 S(1) line (17.03 μm) in the central regions of NGC 6946. The dotted line represents the RSRF of the instrument (see text). The vertical line is the expected wavelength for a heliocentric radial velocity of 48 km s^{-1}.

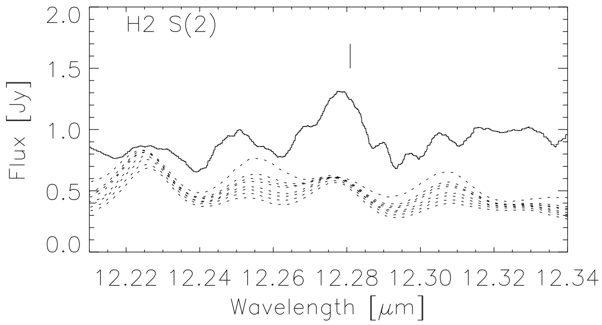

Fig. 2. ISO-SWS spectrum of the H_2 S(2) line (12.28 μm) in the central regions of NGC 6946, with symbols as in Fig. 1.

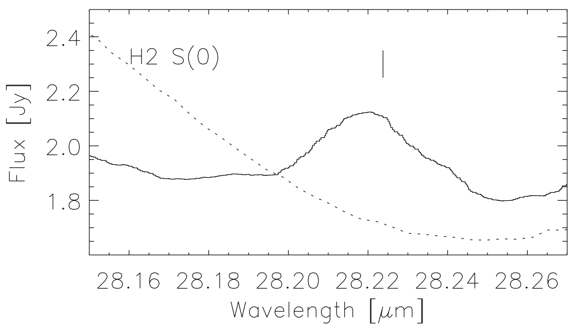

Fig. 3. ISO-SWS spectrum of the H_2 S(0) line (28.21 μm) in the central regions of NGC 6946, with symbols as in Fig. 1.

prefer to adopt an ortho/para ratio of 3, implying $T = 170$ K gas. We note that the adopted ortho/para ratio is also supported by the near-IR spectra presented by Engelbracht et al. (1996) who detect bright ortho-lines but no para-lines.

For these parameters, the observed flux of the S(1) line corresponds to $5 \cdot 10^6 M_\odot$ of warm gas and, averaged over the $5''$ central source, a warm column density of $N(H_2) = 2.3 \cdot 10^{22}$ cm^{-2} or 360 $M_\odot$ pc^{-2}. For a molecular cloud scale height of ~ 50 pc and $n_{H_2} = 10^4$ cm^{-3}, a volume filling factor of $\sim 1\%$ for the warm gas results.

4. Comparison with CO data

High resolution images of ^{12}CO $J = 1 \rightarrow 0$ emission from NGC 6946, presented by Ishizuki et al. (1990) and by Regan and Vogel (1995), reveal an elongated North-South filament in which is embedded a pronounced concentration, about $6''$ in diameter, centred on the nucleus of the galaxy. This central component has a pronounced velocity gradient and contains a total velocity range of about 150 km s^{-1}. Given the agreement in size and velocity dispersion, we conclude that the H_2 emission detected by ISO originates in this component. We note that the size of this region agrees with that of the nuclear star formation region, as shown by the Brγ imaging by Engelbracht et al. (1996). Thus the warm gas component is found only in the nuclear starburst region and not in more extended, quiescent gas. Radiation from massive stars or shocks from *e.g.* supernova explosions in the nuclear complex are therefore the most obvious mechanisms for producing the elevated temperatures.

Ishizuki et al. (1990) compute the total H_2 mass, implied by the CO data, to be $4 \cdot 10^8 M_\odot$, 75% of which is due to the nuclear concentration. However, this result was obtained using a CO/H_2 conversion factor determined for Galactic GMCs, and probably overestimates the true H_2 mass. The fact that the total dynamical mass of gas and stars in the nuclear concentration of NGC 6946 is about $3 \cdot 10^8 M_\odot$, while a significant fraction of this dynamical mass could be stellar, as argued by Engelbracht et al. (1996), also indicates an H_2 mass significantly lower than $3 \cdot 10^8 M_\odot$. A lower limit of $3 \cdot 10^7 M_\odot$ for the total H_2 mass in the central $20''$ (with again 75% or $2.2 \cdot 10^7 M_\odot$ concentrated in the central $5''$ complex) has been obtained by Wall et al. (1993) based on the assumption that the ^{13}CO $J = 1 \rightarrow 0$ line is optically thin. We therefore conclude that the total H_2 mass of the $5''$ central molecular concentration must be significantly higher than $2.2 \cdot 10^7$ and significantly lower than $3 \cdot 10^8 M_\odot$. The $5 \cdot 10^6 M_\odot$ of 170 K molecular gas detected by ISO is therefore of the order of 5–10% of the total molecular mass in the nuclear molecular complex, with formal lower and upper limits of 2 and 20%.

In a study of the $J = 1 \rightarrow 0, 2 \rightarrow 1$ and $3 \rightarrow 2$ lines of ^{12}CO and ^{13}CO with matched $20''$ FWHM beams, Wall et al. (1993) show that two molecular gas components are present in the centre of NGC 6946: a warm ($T > 50 - 100$ K), dense ($n_{H_2} > 10^4$ cm^{-3}) component, and a cooler, somewhat less dense component. While due to the high optical depths of the CO lines, the relative mass proportions of these components cannot be reliably estimated, the warm component should make a significant contribution to the observed ^{13}CO $J = 3 \rightarrow 2$ emission, since this line is expected to be only moderately opaque, and therefore traces the column density of the warm component better than

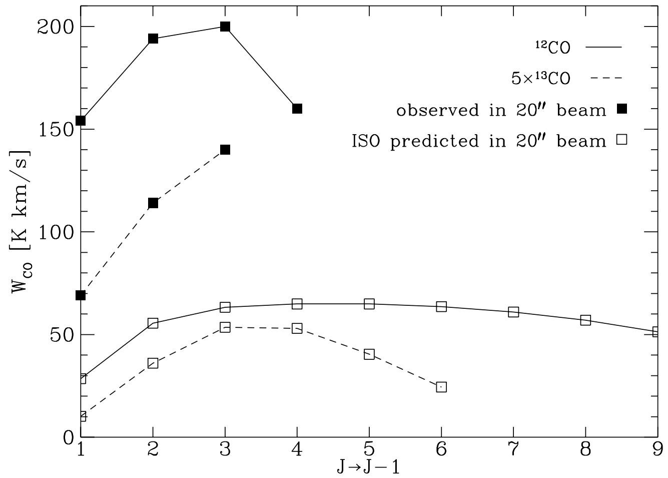

Fig. 4. Integrated brightness temperatures in the lowest CO rotational lines for the 170 K gas detected with ISO, compared to observed values. The predicted values are based on an LVG model with parameters described in the text, and assuming a source of 5″ diameter, observed with a 20″ FWHM beam. The observed data points, all reduced to the same 20″ beam, are from Wild (1990), Sage & Isbell (1991), Wall et al. (1993) and Israel & Van der Werf (1996).

the other lines. We have calculated the contribution due to the gas detected by ISO to the integrated CO emission line strengths in the central region of NGC 6946 using large velocity gradient (LVG) calculations for CO emission from an H_2 column density of $2.3 \cdot 10^{22}\,\mathrm{cm}^{-2}$ at $T = 170\,\mathrm{K}$. Abundance ratios $^{12}CO/H_2 = 10^{-4}$ and $^{12}CO/^{13}CO = 1/30$, similar to the value for the Galactic centre (Langer & Penzias 1990), were assumed. For a density $n_{H_2} = 10^4\,\mathrm{cm}^{-3}$, a cloud line width of $10\,\mathrm{km\,s}^{-1}$, and a source of 5″ diameter observed with a 20″ beam, the resulting integrated line strengths are shown in Fig. 4. The LVG model produces ^{12}CO lines with optical depths of 4 to 9 for most lines, and this result accounts for the weak dependence on rotational quantum number of the ^{12}CO line strengths. Figure 4 suggests that the ^{12}CO $J = 5{\rightarrow}4$ and $J = 6{\rightarrow}5$ lines may be dominated by the 170 K gas. In agreement with Wall et al. (1993), we find that the ^{13}CO lines produced by the warm gas have optical depths less than 1, so that the highest observed transition traces the warm molecular gas best, with 40% of the observed ^{13}CO $J = 3{\rightarrow}2$ line due to the 170 K gas. The agreement in *slope* of the predicted and observed ^{13}CO curves in Fig. 4 suggests that the 170 K gas detected by ISO and the warm component invoked by Wall et al. (1993) are the same gas. In fact, if the ^{13}CO abundance is raised by a factor 1.4, to $5 \cdot 10^{-6}$, or if the intrinsic source size is assumed to be 6″ rather than 5″ (which is allowed by our errors), the agreement in slope is almost exact, and the observed and predicted curves for ^{13}CO in Fig. 4 are only *offset*, by about $12\,\mathrm{K\,km\,s}^{-1}$ for all three observed ^{13}CO lines, independent of rotational quantum number. This agreement suggests a simple two-component model, in which the warm gas detected by ISO is responsible for the *increase* in ^{13}CO integrated line strength from $J = 1{\rightarrow}0$ to $J = 3{\rightarrow}2$ (as shown in Fig. 4), and a cooler component (not detected by ISO) produces an approximately constant integrated line strength of $12\,\mathrm{K\,km\,s}^{-1}$ for the three lowest rotational lines. The ^{13}CO $J = 1{\rightarrow}0$ line is dominated by the cold component and the detected H_2 28 μm flux provides a formal constraint on mass and temperature of the cooler gas: if the cold component contains most of the molecular mass, it must be cooler than 70 K in order not to produce more emission in the S(0) line than observed. We finally note that, as shown in Fig. 4, the warm gas produces only about 20% of the observed ^{12}CO $J = 1{\rightarrow}0$ line, so that the CO/H_2 conversion factor for this line is not strongly affected by the presence of the warm component.

We conclude that 5–10% of the molecular mass in the central molecular complex in NGC 6946 is warm with $T = 170$ K, most likely as a result of heating by the nuclear starburst. This warm gas fully accounts for the warm component indicated by CO data, and the present ISO data provide a straightforward mass determination for this component. The CO/H_2 conversion factor for ^{12}CO $J = 1{\rightarrow}0$ is not strongly affected by the presence of the warm component.

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