THE ISO-SWS SURVEY FOR MOLECULAR HYDROGEN IN GALAXIES*

E.A. Valentijn[1], **P.P. van der Werf**[2]

[1]SRON and Kapteyn Institute, Groningen, The Netherlands
[2] Sterrewacht Leiden, The Netherlands

ABSTRACT

ISO-SWS has made the first extragalactic direct detection of the H_2 molecule in pure rotational lines in the nucleus of NGC 6946. Here we focus on the interstellar medium in the *disks* of spiral galaxies. Our detection (Valentijn & van der Werf 1999, hereafter VW99) of the two lowest pure rotational lines of molecular hydrogen at 28.2 (S(0)) and 17.0 μm (S(1) at 8 positions throughout the stellar disk of NGC 891 provides new insight in atomic to molecular hydrogen ratios and the physical state of the interstellar medium in the disks of late-type galaxies. H_2 has been detected out to 12 kpc from the center of NGC 891. The data indicate relatively warm ($T = 150 - 230$ K) molecular clouds scattered throughout the disk, in addition to a massive cooler ($T = 80 - 90$ K) component which dominates in the outer regions. For H_2 ortho-para ratios of 2–3 the cool component has typical edge-on surface densities of about $3000\,M_\odot/pc^2$, in which case it outweighs the atomic hydrogen by a factor 10. This factor raises the gas masses within the optical disks sufficiently to account for the observed rotation curves in these regions.

Key words: ISO-SWS; Molecular Hydrogen; ISM.

1. INTRODUCTION

Molecular gas masses in spiral galaxy disks are notoriously difficult to measure, and usually depend on indirect measurements based on other tracers such as the CO molecule or dust. Figure 1 schematically highlights some of the key issues in this field. The principal components of the interstellar medium (ISM) are HI, H_2, and dust. The HI content is well known and its distribution is more extended than that of the stars. Applying the Galactic "extinction to HI ratio" ($A_V/N(\mathrm{HI})$) to HI images of galaxies, a relatively high dust content in the outer regions is found, as is also concluded from optical extinction studies using inclination tests (e.g., Valentijn 1990). This dust was not detected by IRAS, which was only sensitive to warmer, more centrally located dust. It is, however, now detected by ISOPHOT, as testified by several papers in these proceedings reporting $T = 10 - 20$ K dust, with masses 10–20 times higher than detected by IRAS. Most importantly, Alton et al. (1998a) find a 200 μm scalelength almost a factor two larger than the IRAS scalelength. This indicates a *cold* dust component more extended than the stellar component, which is also the case for the HI distribution. This is confirmed by recent SCUBA observations (Alton et al. 1998b). Thus both recent far-infrared and submillimetre photometry and optical extinction studies appear to indicate a dust component with a radial scalelength larger than that of the stars, such as is also the case with the HI. The question arises how this compares to the molecular gas component. ISO allows a direct measurement of molecular hydrogen through its purely rotational transitions, without having to resort to indirect tracers such as CO, which rely on a standard "CO to H_2 conversion ratio" (determined for an ensemble of *Galactic* giant molecular clouds) and hence are fraught with uncertainties. Characterizing the H_2 component independent of CO data was the principal goal of the ISO-SWS survey for molecular hydrogen in galaxies.

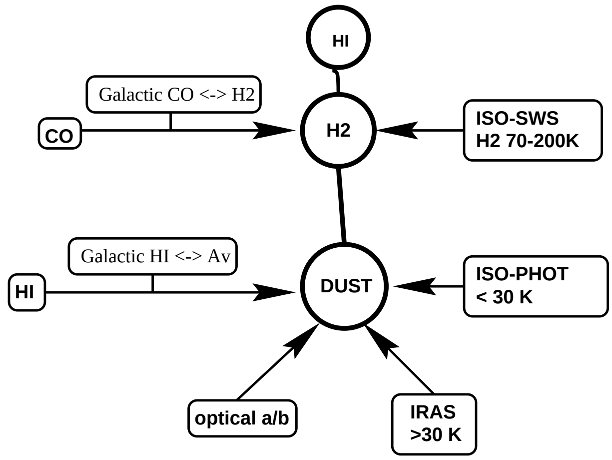

Figure 1. Components of the interstellar medium and their tracers.

*ISO is an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA.

2. OBSERVING H_2 IN GALAXIES WITH ISO-SWS

2.1. H_2 rotational 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 of H_2 consists of an ortho (J odd) and a para (J even) series of weak quadrupole transitions. ISO's SWS (De Graauw et al. 1996) provides a unique possibility to observe moderately warm H_2 directly in the lowest purely rotational transitions S(0): $J_\mathrm{u} - J_\mathrm{l} = 2 - 0$ at 28.2188 μm (para) and S(1) : $J_\mathrm{u} - J_\mathrm{l} = 3 - 1$ at 17.0348 μm (ortho). The ortho/para ratio (hereafter o/p) will be three if set by the ratio of statistical weights.

2.2. NGC 6946

The first extragalactic detection of these lines was obtained in the central, relatively warm and star forming region of the nearby face-on spiral galaxy NGC 6946 (Valentijn et al. 1996), and in fact this paper contains the first published spectrum of the lowest (S(0), 28 μm) transition of H_2 in any object outside the solar system; we refer to this paper for further details of our survey. Observed line ratios (S(0)/S(1)$\sim$ 0.15) indicate a temperature of this gas component of 170 K for an ortho/para ratio of 3, corresponding to the ratio of statistical weights. When combined with the observed line flux this leads to a mass of $5 \cdot 10^6\,\mathrm{M}_\odot$. A significant upper limit on the S(2) (12.3 μm- para) line flux was used to constrain the o/p ratio to ≥ 2, a value which is also commonly found for PDRs. 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.

Since this paper was published, we have surveyed NGC 6946 at one more position, about 4 kpc East of the nucleus. We have detected both S(0) and S(1) with a significantly higher line ratio (S(0)/S(1)$\sim$ 1), and a flux of $\sim 5 \cdot 10^{-17}\,\mathrm{W\,m^{-2}}$ for both lines (see Fig. 2). Assuming local molecular gas densities based on other molecular tracers we derive a temperature around $130 - 170$ K, which is similar to the relative warm component detected in the disk of NGC 891 (see next Section).

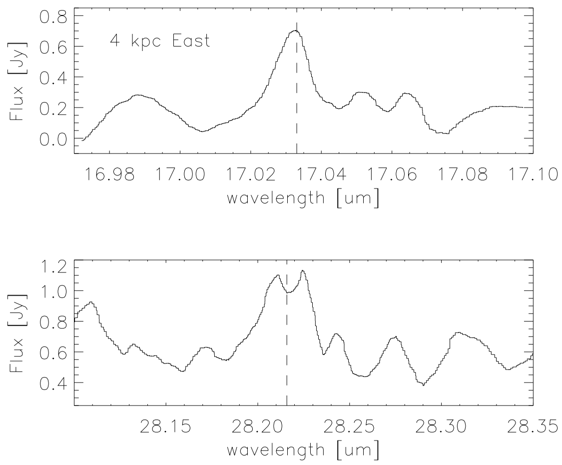

Figure 2. ISO-SWS detection of H_2 S(0) and S(1) in the disk of NGC 6946, 4 kpc East of the nucleus. The dashed lines indicate the expected wavelength of the line, given the radial velocities determined from CO data.

2.3. H_2 in the disk of NGC 891

In the nearby edge-on galaxy NGC 891 we observed the S(0) and S(1) lines at the centre and at 7 positions along the galaxy major axis, out to a radius of 11 kpc (assuming a distance to NGC 891 of 9.5 Mpc). We integrated for about 1500 sec on each line, except at the position at 11 kpc North where we integrated in total for $\sim$ 4 hours. We have detected both lines at each of the surveyed positions, even at the outermost position at 11 kpc, where CO is barely detected.

In Figs. 3 and 4 we show our observations at some of the outer positions. In Fig. 5 (from VW99) the rotation curve in H_2 of NGC 891 is compared with CO data. The accuracy of the wavelength calibration corresponds to about 20 km/sec. Since the SWS slitwidth of 20$''$ at S(0) and 14$''$ at S(1) is a factor 2–3 larger than the diffraction beam, an offset of a point source of 4$''$ on the slit causes a wavelength shift corresponding to 41 km/sec at S(1) and 53 km/sec at S(0). When allowing for such small shifts the observed rotational velocities match well to the CO data.

In Fig. 5 we also compare the radial H_2 S(0) and S(1) profiles with the CO profile. Remarkably, the S(1) line follows more or less the CO profile, while the S(0) line shows an excess at larger radii, indicating a larger radial scale length, like the HI gas and the cool dust detected with SCUBA. At the outer positions, the S(1) lines originate from unresolved compact sources; this is not the case for the S(0) line: Figs. 3 and 4 indicate that the S(0) emission originates from extended (slit filling) regions. These line profiles imply that S(1) traces unresolved warm regions scattered throughout the disk, but more common in the inner regions, while S(0) traces a cooler and more pervasive component (see VW99 for details).

We have compared these results with models of the collisional excitation of H_2 as well as information from other tracers. We conclude that at $r < 6$ kpc the H_2 emission is dominated by relatively warm clouds ($T = 130 - 230$ K) with $n_{\mathrm{H}_2} \sim 200 - 2000\,\mathrm{cm}^{-3}$ and $N_{\mathrm{H}_2} \sim 10^{22}\,\mathrm{cm}^{-2}$, with a factor 3 times higher

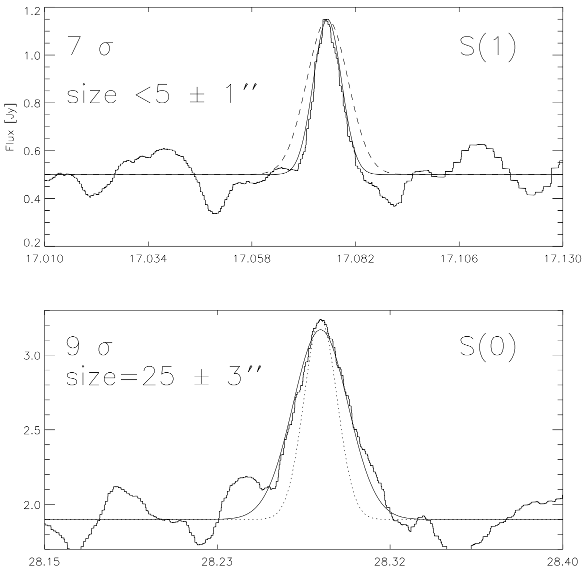

Figure 3. ISO-SWS line profiles of H_2 S(0) and S(1) in the disk of NGC 891, 8 kpc South of the nucleus, together with Gaussian fits to the profiles (solid lines). The dotted line represents the theoretical line profiles for a source extent $\leq 5''$ perpendicular to the slit, identical to the fit for S(1). The long dashed line represents the theoretical profile for a source extent filling the slit (identical to fit for S(0)).

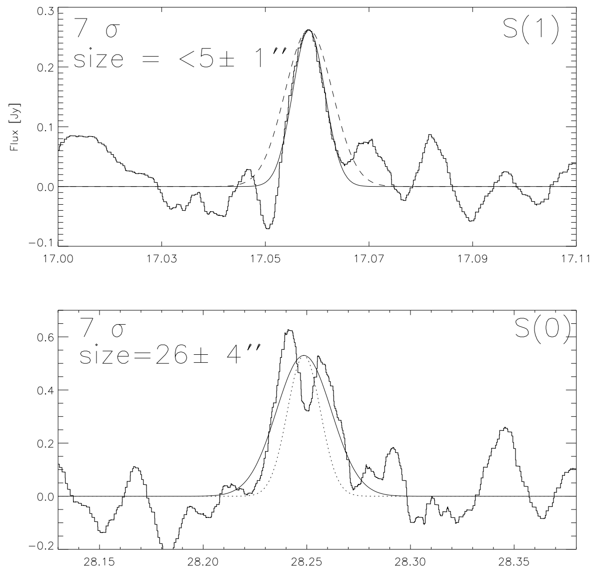

Figure 4. ISO-SWS line profiles of H_2 S(0) and S(1) in the disk of NGC 891, 11 kpc North of the nucleus. Line profiles are coded as in Fig. 3. Also here the S(1) profile matches to that of a point source, while the S(0) profile corresponds to that expected from a slit filling source.

$N_{\mathrm{H_2}}$ in the nuclear region. Interpolating our measurements and integrating over the whole $r < 6$ kpc region, these values corresponds to $\sim 2 \cdot 10^9 \mathrm{M}_\odot$ of warm H_2, roughly half of the mass deduced from CO data (e.g., Sakomoto et al. 1997) in the same region. Given its temperature and density, this large amount of warm gas can be identified with UV-heated outer layers of molecular clouds throughout the inner disk of NGC 891, where CO may be photodissociated. This interpretation is in agreement with the detection of extended [CII] 158 μm emission in NGC 891 (Madden et al., 1994) originating in warm extended photodissociation regions (PDRs). These PDRs thus contain a significant fraction of the gas mass in the inner disk of NGC 891.

For the outer positions, the observations require a cooler ($80-90$ K) and pervasive (i.e., slit filling) component, which is also radially more extended than the warm component and the stellar distribution in NGC 891 (see VW99 for details). A total edge-on column density in the range $1-3\cdot 10^{23}\,\mathrm{cm}^{-2}$ (i.e., $1600-5500\,\mathrm{M}_\odot/\mathrm{pc}^2$) is implied, with $n_{\mathrm{H_2}}$ around a few hundred cm^{-3} and temperatures in the range $80-90$ K. For these computations we used o/p=2, resulting in about a factor two lower mass than for o/p=3. Thus, our data indicates a massive H_2 component in the disk of NGC 891 and in the next Section we further discuss our observations of this cooler $80-90$ K component.

3. DISCUSSION

3.1. Robustness of results

A crucial step in our analysis is the conclusion that the S(0) and S(1) lines trace separate components of the ISM. If instead a 1-component solution was adopted (accounting for both the S(0) and S(1) emission), the derived temperature would be $100-130$ K, density $n_{\mathrm{H_2}} \sim 200\,\mathrm{cm}^{-3}$ and the implied masses significantly lower, although still substantial. In this case we would identify this gas with the photodissociated outer layers of molecular clouds also detected in [CII] 158 μm emission and indeed the derived masses agree well with those derived from the [CII] data of Madden et al. (1994). However, the disparity of the line profiles indicate that this model is too simple and suggest a 2-component solution with a warm component dominating S(1) and a cool component dominating S(0), with parameters and implications as discussed in the previous section. Given that this conclusion ultimately depends on the quality of the line profiles, we discuss below the robustness of these results.

The significance of the disparity in line profiles is well illustrated by Figs. 3 and 4. We have built special filter routines to remove the effect of the cosmic rays near the noise level (Valentijn & Thi, 1999), which resulted in nearly gaussian noise, a factor of 3–4 lower than obtained with the standard pipeline routines. Our results have been checked for stability when applying different filter values. Furthermore, the result at the outer positions of NGC 891, of unresolved S(1) and slit-filling S(0), has consistently been obtained at

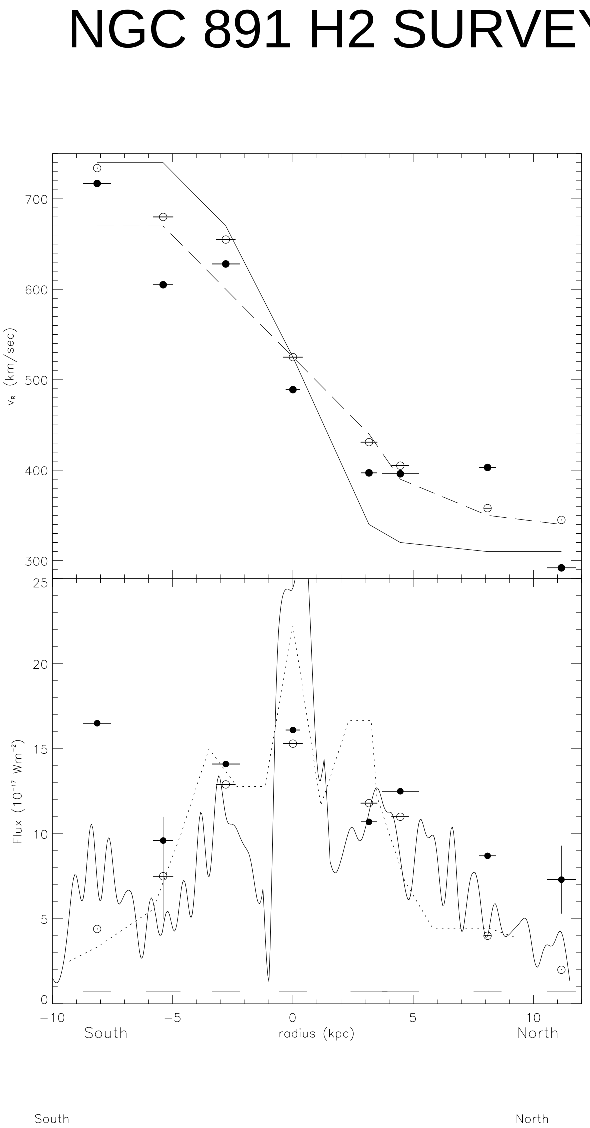

Figure 5. Observations of H_2 S(0) (filled circles) and S(1) (open circles) at various positions along the major axis of NGC 891. The size of the emitting regions, projected along the major axis, are indicated by horizontal bars through the data points. The horizontal bars at the bottom of the figure indicate the size of the SWS aperture (for S(0)) projected along the major axis. Top panel: heliocentric radial velocities, the lines indicate the approximate maximum and minium rotational velocities from ^{12}CO (Sakamoto et al. 1997). Bottum panel: total linestrength, with ^{12}CO intensity profiles (drawn line from Sakamoto et al. 1997, dashed line from Scoville et al., 1993) arbitrary scaled to best fit the S(1) data in the disk (nuclear point excluded). The exceptionally large errors of two S(0) lines, observed late in the ISO mission with aged detectors, are indicated by a vertical bar.

all three positions. Finally, the SWS line profile has been extensively characterized in the laboratory and in orbit on both extended sources and point sources, and fully support the adopted theoretical profiles as used in Figs. 3 and 4. We thus conlude that these results are robust and are not affected by uncertain or poorly characterized instrumental effects.

3.2. Relation to other ISM components

Since the temperature of the gas detected here ($T \sim 80$ K) is close to the upper level temperature (91 K) of the [CII] 158 μm transition, this molecular gas should emit strongly in [CII] if most of the carbon was in the form of C^+. Remarkably, the observed [CII] emission (Madden et al. 1994) is a factor 5–10 too low. This discrepancy is in line with other reports of underluminous [CII] emission at this conference and in the recent literature. An interesting possibility is that a lower C^+ abundance, or alternatively optically thick [CII], might account for the existence of the $80-90$ K gas: the absence of effective [CII] cooling would lead to an elevated temperature. We also note that unlike the Milky Way, radio synchrotron radiation from the disk of NGC 891 is intense, and the resulting enhanced cosmic ray heating may also be responsible for the elevated temperatures derived here.

Our data are confined to the stellar disk of NGC 891, and do not extend into the outer regions of the HI disk, where the mass discrepancy indicated by the rotation curve is most prominent. However, the cooler H_2 component detected here has a scale length which is more extended than the CO or the stellar component, like the HI and the cold dust component. Furthermore, within the outer stellar disk analysis of high-quality rotation curves indicates that a mass discrepancy also exists also in these regions, and Burkert & Silk (1997) propose that this matter could be in the form of unseen baryons, in agreement with our results.

We finally note that Alton et al. (1998b) deduce a total cold (15 K) dust mass at $r < 11$ kpc of $5 \cdot 10^7\,M_\odot$, which is only a factor 10 less than the HI mass found from 21 cm line work (Swaters et al. 1998). However, when the H_2 mass derived here is taken into account, the total gas to dust ratio is ∼200, close to the Galactic value.

REFERENCES

Alton, P.B., Trewhella, M., Davies, J.I., Evans, R. et al., 1998a, A&A, 335, 807

Alton, P.B., Bianchi, S., Rand, R.J., Xilouris, E.M. et al., 1998b, ApJ, 507, L125

Burkert, A., & Silk, J. 1997, ApJ, 488, L55

Graauw, de Th. et al.. 1996, A&A.315, L49

Madden, S.C., Geis, N., Genzel, R., Herrmann, F. et al., 1994, Infrared Phys. Technol., 35, 311

Sakamoto, S., Handa, T., Sofue, Y., Honma, M. & Sorai K., 1997, ApJ, 475, 134

Scoville, N.Z., Thakkar, D., Carlstrom, J.E. & Sargent, A.I., 1993, A&A, 404, L59

Swaters, R.A., Sancisi, R., & van der Hulst, J.M., 1998, ApJ, 491, L114

Valentijn, E.A., 1990, Nature, 346, 153

Valentijn, E.A., Van der Werf, P.P., Graauw, Th., & de Jong, T. 1996, A&A 315, L145

Valentijn, E.A. & Thi, W.F., 1999, Experimental Astronomy. in press

Valentijn, E.A. & Van der Werf, P.P., 1999 submitted