THE *ISO*–SWS 2.4–45.2 MICRON SPECTRUM TOWARD ORION IRC2¹

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Received 1998 April 3; accepted 1998 May 27; published 1997 July 9

ABSTRACT

The complete infrared spectrum from 2.4 to 45.2 μm toward the prototypical massive star-forming region Orion IRC2 is presented, obtained with the Short Wavelength Spectrometer (SWS) on board the *Infrared Space Observatory* (*ISO*) at a resolving power $\lambda/\Delta\lambda \approx 1300$ –2500. A wealth of emission and absorption features is found, including H_2 vibration-rotation lines, the full set of H_2 pure rotational lines (0,0) $S(1)$ – $S(17)$, H recombination lines, ionic fine-structure lines, PAH emission features, and absorption and emission bands by interstellar ices and gas-phase molecules, including CO_2 , CH_4 , and SO_2 . Particularly interesting is the detection of strong emission and absorption lines in the H_2O ν_2 bending mode at 6.2 μm and the observation of highly excited pure rotational lines of H_2O in absorption at 25–45 μm . The origin of these lines in each of the physical components included in the *ISO*–SWS beam (H II region, PDR, quiescent ridge, shocked low-velocity plateau) is briefly discussed.

Subject headings: infrared: ISM: lines and bands — ISM: abundances — ISM: molecules —
 ISM: individual: (Orion IRC2) — molecular processes

1. INTRODUCTION

The Orion IRC2 region is the best studied area of massive star formation in the Galaxy and serves as the principal template for more distant star-forming regions in external galaxies. Because of its proximity and extraordinary brightness, it has been the prime target for most of the pioneering observations at infrared and millimeter wavelengths, which have played a pivotal role in our understanding of the formation of massive young stars (see, e.g., Genzel & Stutzki 1989; Blake 1997). Much of the complexity of these regions is the result of the disruption of their environment by powerful outflows (see, e.g., Vogel et al. 1984; Draine & McKee 1993), and by intense ultraviolet radiation dissociating and ionizing the gas on the cloud surfaces (see, e.g., Stacey et al. 1993; Hollenbach & Tielens 1997). The bulk of the line and continuum emission emanates at infrared wavelengths, so that high-quality mid- and far-infrared spectra are essential to probe the physics and chemistry of massive star-forming regions. The *Infrared Space Observatory* (*ISO*) provides the first opportunity to obtain the complete infrared spectrum from 2.4 to 197 μm unimpeded by Earth's atmosphere, and we present here the first results of our observations obtained with the SWS in the 2.4–45.2 μm range (de Graauw et al. 1996).

The SWS aperture varies from $14'' \times 20''$ at the shorter wavelengths to $20'' \times 33''$ at the longer wavelengths. Several different physical components have been identified in the central $\sim 30''$ region surrounding Orion IRC2 (see, e.g., Genzel & Stutzki 1989; see Fig. 7 of Haas, Hollenbach, & Erickson

1991). The overall geometry consists of an extended ridge of quiescent, warm, and dense gas in the NE–SW direction, which contains a clumpy cavity of $\sim 10^{17}$ cm ($\sim 15''$) diameter located near IRC2. The Trapezium stars, in particular $\theta^1\text{C Ori}$, irradiate the front side of the molecular cloud, resulting in an ionized and a neutral photon-dominated region (PDR) along the line of sight toward the observer. IRC2 itself is highly extinguished because of the “hot core” centered $\sim 2''$ south of IRC2, consisting of a collection of hot and dense clumps each of size $\sim 1''$, which are optically thick in the mid- and far-infrared continuum. Infrared studies at 2–30 μm reveal numerous objects in this area (see, e.g., Wynn-Williams et al. 1984; Gezari 1992), although most of the structure seen in the maps is a result of scattering and reprocessing of radiation in an inhomogeneous region with patchy extinction by the surrounding envelope. BN (located $\sim 7''$ NW of IRC2), source “I” (located $\sim 0''.5$ – $1''$ south of IRC2), and source “n” (located $2''.5$ south of IRC7) appear to be the only self-luminous massive young stellar objects contained in the *ISO*–SWS beam (Menten & Reid 1995). The outflow(s) streaming away from the embedded source can be distinguished into the low-velocity flow extended over $\sim 20''$ in the NE–SW direction along the ridge, and the high-velocity flow extended in the NW–SE direction. The latter flow plunges into the surrounding cloud $\sim 30''$ from the dynamical center, resulting in the well-known “peak I” and “peak II” shocked regions seen in the H_2 (1,0) $S(1)$ emission line (see, e.g., Beckwith et al. 1978; Chrysostomou et al. 1997; Stolovy et al. 1998). Most of these components except peak I and II are present in the SWS aperture.

One of the prime species for observation with the SWS is the H_2O molecule. In the SWS wavelength range, both the vibration-rotation bands at 2.7 and 6.2 μm and the higher lying pure rotational lines at 20–45 μm are to be found. H_2O is particularly powerful for probing the interaction of massive stars with their surroundings because its abundance is greatly enhanced in warm regions and shocks (see, e.g., Kaufman & Neufeld 1996; Charnley 1997) and because its level populations are influenced by mid- and far-infrared radiation from warm dust, in addition to collisions (see, e.g., Phillips et al. 1978). The *ISO*–SWS observations provide important complementary information to previous ground-based and airborne observa-

¹ Based on observations with *ISO*, an ESA project with instruments funded by ESA Member States (especially the PI countries France, Germany, the Netherlands, and the United Kingdom) and with participation of ISAS and NASA.

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FIG. 1.—Complete *ISO*-SWS grating spectrum centered at Orion IRC2. The principal absorption and emission features are indicated. Inset shows a blowup of the 40–45 μm region, in which several gas-phase H_2O absorption lines can be seen (40.69 μm , o- H_2O $4_{32}-3_{03}$; 43.89 μm , o- H_2O $5_{41}-4_{32}$; 44.19 μm , p- H_2O $5_{42}-4_{31}$; 45.11 μm , o- H_2O $5_{23}-4_{14}$).

tions of H_2O (see, e.g., Cernicharo et al. 1994; Zmuidzinas et al. 1995; Tauber et al. 1996; Timmermann et al. 1996; Genheimer, Mauersberger, & Wilson 1996): the beam is comparable to that of the large single-dish submillimeter observations, but since the hot core is optically thick at mid-infrared wavelengths, only foreground emission and/or absorption is probed with the *ISO*-SWS. The data also complement the earlier observations by Knacke, Larson, & Noll (1988) and Knacke & Larson (1991) of H_2O absorption lines in the ν_3 vibrational band at 2.7 μm toward BN.

In this Letter, we present an overview of the features found in the *ISO*-SWS spectrum toward Orion IRC2, whereas radiative transfer models of H_2O are described in the accompanying paper by González-Alfonso et al. (1998). More detailed discussions of selected parts of the spectrum will be given in future papers by Wright et al. (1998) and Boonman et al. (1999). Complementary observations with the *Long Wavelength Spectrometer* (LWS) are presented in Cernicharo et al. (1997, 1998) and Harwit et al. (1998).

2. OBSERVATIONS

Complete grating scans from 2.4 to 45.2 μm at the highest spectral resolution $\lambda/\Delta\lambda \approx 1300$ –2500 using the SWS06 mode were made on 1997 September 6 (revolution 660) centered at $\alpha(1950) = 05^{\text{h}}32^{\text{m}}46^{\text{s}}.8$, $\delta(1950) = -05^\circ 24' 25''$, which is $\sim 3''$ west, $2''$ south of the IRC2 position listed by Gezari (1992). The beam was oriented $\sim 7^\circ$ in the NW–SE direction, covering both IRC2 and BN. The SWS beam profiles indicate that the response drops to $\sim 20\%$ at $\sim 10''$ offset from center (Schaeidt et al. 1996).

Data reduction was carried out on the standard processed data file from the Off Line Processing system, using standard routines within the SWS interactive analysis package. The high continuum flux encountered in band 4 (29–45 μm), and the finite response time of the detectors, lead to a significant memory effect near the band edges—positions of important water

and OH lines—and so necessitated an up-down correction. Small shifts up to 20% have been applied to adjacent bands to produce a continuous spectrum. Although the most up-to-date calibration files have been used, small problems remain with the spectral shape around 28, 33, and perhaps 11 μm . The broad, weak features seen at these wavelengths correspond to features in the relative spectral response calibration files of the SWS (see, e.g., Leech et al. 1998⁹). The continuum fluxes and [Si II] 34 μm and H_2 17 μm line fluxes agree with those of Haas et al. (1991) and Burton & Haas (1997), taking into account the different beam sizes and complex structure of the region.

3. RESULTS

In Figure 1, the full *ISO*-SWS spectrum centered on Orion IRC2 is presented. The spectrum rivals that of other well-known sources such as Sgr A* (Lutz et al. 1996) in terms of complexity and number of features. The global continuum shape is caused by emission from warm, $T_d = 75$ –300 K dust (see, e.g., Wynn-Williams et al. 1984). A large number of emission and absorption features are seen superposed on the strong continuum, which will be briefly discussed. The fluxes of the strongest lines are summarized in Table 1; the uncertainties are dominated by the uncertainties in the flux calibration of the SWS, which range from $\sim 5\%$ at the shortest wavelengths to $\sim 30\%$ at the longest wavelengths (Schaeidt et al. 1996; Leech et al. 1998).

H_2 vibration-rotation and pure-rotation lines.—At the shortest wavelengths between 2.4 and 3.5 μm , a forest of emission lines is seen, most of which result from the H_2 low- and high- J Q - and O -branch lines in the $(v', v'') = (1, 0)$ vibrational band. At longer wavelengths, the pure rotational lines in the (0,0) band of H_2 are prominent, with lines up to (0,0) $S(17)$ detected. Some of these have also been seen in ground-based observations of Orion (see, e.g., Beck 1984; Brand et al. 1989; Parmar,

⁹ Also available on-line at http://isowww.estec.esa.nl/manuals/sws_idum/.

TABLE 1
FLUXES OF SELECTED EMISSION LINES^a

Species	Wavelength (μm)	Flux ($10^{-18} \text{ W cm}^{-2}$)
HI Br α	4.052	6.3
[Ar II]	6.985	2.8
[Ar III]	8.991	14.0
[S IV]	10.51	17.5
[Ne II]	12.81	45.4
[Ne III]	15.55	63.5
[P III]	17.88	0.40
[Fe II]	17.94	0.25
[S III]	18.71	53.7
[S I]	25.25	5.4
[S III]	33.48	29.5
[Si II]	34.81	11.2
[Ne III]	36.00	6.0
H ₂ 1-0 Q(3)	2.424	1.55
H ₂ 1-0 O(5)	3.235	0.68
H ₂ 0-0 S(2)	12.28	3.2
H ₂ 0-0 S(1)	17.03	1.0

^a Fluxes not corrected for extinction.

Lacy, & Achtermann 1994; Burton & Haas 1997), but several are observed for the first time at IRC2. The strong continuum and severe fringing at 28 μm prevent the detection of the (0,0) S(0) line at the grating resolution. Most of the H₂ emission likely arises in the shocked plateau gas, with possibly a small contribution from the PDR. The excitation temperature characterizing the pure rotational lines up to $J = 9$ is $750 \pm 50 \text{ K}$ compared with $2000 \pm 200 \text{ K}$ for the vibration-rotation lines, correcting the observed fluxes for $A_V \approx 20 \text{ mag}$ of extinction (Wright et al. 1998).

Ionic lines.—The ionized gas in front of IRC2 is probed mostly through the H recombination as well as the ionic fine-structure lines. Lines of [Ar II] 6.99 μm , [Ar III] 8.99 μm , [S IV] 10.51 μm , [Ne II] 12.81 μm , [Ne III] 15.55 and 36.01 μm , and [S III] 18.71 and 33.5 μm are prominently seen in the spectrum. In general, the observed fluxes match well the predictions of the best fit model of Orion by Rubin et al. (1991) at the projected distance from $\theta^1 \text{C}$. Some of the fine-structure emission, such as the [Ne II] 12.8 μm , [S I] 25.2 μm and [Si II] 34.8 μm lines can also arise in the Orion shock and/or PDR (Haas et al. 1991). Together with the H₂ lines, they can be used to determine the relative contributions from J- and C-shocks and thereby test the models (Wright et al. 1996, 1998).

Solid state features and gas-phase molecules.—A number of broad emission bands are present, particularly at 3.3 and 6.2 μm , with weaker features at 8.6 and 11.3 μm . These are the well-known UIR bands identified with large molecules, presumably PAHs, and plausibly originate in the PDR at the front side of the cloud (Tielens et al. 1993). Several broad absorption features are seen that can be ascribed to silicates and H₂O-ice, CO₂-ice, and other ices along the line of sight to the continuum. The ices arise primarily in the colder ($T \approx 50 \text{ K}$ or less) regions of the quiescent extended ridge. Gas-phase CO absorption and possibly emission is seen between 4.4 and 4.8 μm , previously observed by Scoville et al. (1983) toward BN and by Evans, Lacy, & Carr (1991) toward IRC2. Narrow absorption features caused by gas-phase C₂H₂ at 13.7 μm , HCN at 14 μm , and CO₂ at 15.0 μm are clearly detected as well. As found in other warm massive star-forming regions, most of the CO along the line of sight is in the gas phase, whereas most of the CO₂ is in the solid phase (van Dishoeck et al. 1996). In contrast, the gas-phase CH₄ ν_2/ν_4 Q-branch at 7.66 μm is seen in emission, as well as a feature at 7.348 μm . The latter position is close

FIG. 2.—Enlargement of the ISO-SWS spectrum toward IRC2 in the 5.3–7.8 μm range, showing the H₂O ν_2 vibration-rotation lines, as well as the CH₄ ν_2/ν_4 and the SO₂ ν_3 bands in emission.

to that of [Ni III] 7.348 μm , but the shape of the feature suggests a Q band of a molecule, with P- and R-band structure visible on either side (see Fig. 2). The feature can plausibly be ascribed to the SO₂ ν_3 band at 7.348 μm (see simulated spectra by Helmich 1996), a molecule that is known to be prominent in the Orion plateau (Blake 1997). The excitation and abundance of these gas-phase molecules will be discussed by Boonman et al. (1999).

H₂O absorption and emission.—The most surprising results are found in the wavelength ranges that were inaccessible prior to ISO, in particular the 5.3–7.8 μm and 25–45 μm regions. At 25–45 μm , over a dozen pure rotational lines of H₂O are unexpectedly seen in absorption, together with the OH 28.94 and 34.6 μm features (see Fig. 1, inset). These lines arise from levels 200–700 K above ground and likely originate in the shocked plateau gas in front of IRC2. A detailed discussion of these features, together with high-resolution Fabry-Perot observations of selected lines, will be presented by Wright et al. (1998). Figure 2 shows a blow-up of the spectrum between 5.3 and 7.8 μm . Apart from the broad 6.0 and 6.8 μm absorption bands caused by interstellar ices, the broad 6.2 μm PAH feature, a number of strong H₂ and ionic lines and the CH₄ and SO₂ emission bands, all other features can be ascribed to H₂O lines in the ν_2 6.2 μm bending mode in emission. So far, this band has only been detected in absorption in a number of massive warm, star-forming regions (see, e.g., van Dishoeck & Helmich 1996; Dartois et al. 1998). The only lines that clearly appear in absorption toward IRC2 are those arising from the ground 1₀₁ level of ortho-H₂O, although additional absorption lines are seen in the ISO spectrum toward BN (González-Alfonso et al. 1998). The total flux in the H₂O ν_2 emission lines is $2.3 \times 10^{-17} \text{ W cm}^{-2}$, not corrected for reddening. Weak emission in the H₂O ν_3 asymmetric stretching mode at 2.7 μm is seen as well, together with possible absorption. The total flux in the emission lines is $7 \times 10^{-19} \text{ W cm}^{-2}$.

Which physical component is responsible for the H₂O 6 μm emission? The radiative transfer models by González-Alfonso et al. (1998) show that the emission and absorption naturally arises from absorption of 6 μm continuum photons followed by spontaneous emission to the ground state in a gas with $T \approx 150 \text{ K}$ and $n(\text{H}_2) \approx 10^6 \text{ cm}^{-3}$. Some collisional excitation in hotter ($T \approx 400 \text{ K}$) and denser gas may play a role as well.

The inferred H_2O column density is of order a few 10^{17} cm^{-2} . These conditions eliminate the extended ridge gas. Since the continuum radiation from the hot core is optically thick at $6 \mu\text{m}$, this component is also excluded: the lines must be formed in front of the hot core. The H_2O column density in the Orion face-on PDR is predicted to be typically 10^{16} cm^{-2} in the models of Sternberg & Dalgarno (1995) and Jansen et al. (1995) and is not sufficient to explain the observed emission. The most likely candidate is therefore the shocked plateau gas caused by the interaction of the low-velocity outflow with the extended ridge.

The Orion shock has been modeled by Kaufman & Neufeld (1996) with a 37 km s^{-1} flow impacting on a cloud with a preshocked gas density of 10^5 cm^{-3} and a geometrical covering factor of 3. At high temperatures of more than 1000 K, all oxygen is driven into H_2O . Harwit et al. (1998) have recently found confirmation for this model by *ISO*–LWS observations of several H_2O emission lines. The Kaufman & Neufeld (1996) models correctly predict that the H_2O $6.2 \mu\text{m}$ emission should be detectable in shocks. However, for shock velocities of 20–40 km s^{-1} and preshocked gas densities of 10^5 cm^{-3} , their computed total H_2O $6 \mu\text{m}/\text{H}_2(0,0) S(5)$ ratios range from 0.01 to 0.04, considerably lower than our observed ratio of ~ 5 . The discrepancy is caused by the fact that no continuum radiation is taken into account in the excitation or line formation in the shock models (see González-Alfonso et al. 1998).

A small fraction of the $6.2 \mu\text{m}$ absorption may arise from H_2O in the lowest levels in the colder, quiescent ridge cloud (Knacke & Larson 1991), but high spectral resolution observations are needed to derive accurate column densities and abundances for this component.

4. CONCLUSIONS

The *ISO*–SWS spectrum of Orion IRc2/BN provides a powerful demonstration of the complexity of massive star-forming regions, with several physical components present in the SWS aperture. The current data set has the big advantage over earlier studies that all lines are obtained with the same instrument, unhindered by the atmosphere. Comparison with similar data obtained at the peak I and II positions, where the shock emission is stronger but the background continuum weaker, will be very interesting to disentangle the various components. Much more sophisticated radiative transfer models that include non-spherical geometries are required, however, to interpret both the continuum and line data, and analyze the conditions under which the lines appear in absorption or emission. This will be particularly important for a full understanding of the H_2O excitation and abundance in the various physical components. Altogether, the Orion IRc2/BN region continues to provide a unique laboratory for testing theories and developing infrared diagnostics, which can eventually be applied with more confidence to distant regions.

The authors are grateful to the SWS instrument teams in Groningen and Garching and to the SIDT in Vilsbiburg for making these observations possible. They are indebted to G. A. Blake, A. Boonman, F. van der Tak, D. A. Neufeld, G. Melnick, M. Kaufman, and A. G. G. M. Tielens for useful discussions. This work was supported by NFRA/NWO grant 781-76-015 and by the Spanish DGES grant PB96-0883 and PNIE grant ESP97-1618-E.

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