# ISO FIRST RESULTS

**See also the chapters by Tielens & Whittet, Henning, d'Hendecourt and Waters**

# INFRARED SPECTROSCOPY WITH THE INFRARED SPACE OBSERVATORY

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**Abstract.** The Infrared Space Observatory (ISO) is opening the 2.5 to 200 $\mu$m band for detailed infrared spectroscopy. Concentrating on ionic and molecular emission lines observed with the Short Wavelength Spectrometer (SWS) we discuss ISO's first results on Galactic and extragalactic sources.

## 1. Introduction

The infrared waveband (1 to a few hundred $\mu$m) is a very important window for the exploration of interstellar, circumstellar and stellar environments in our and external galaxies. At these wavelengths it is possible to probe regions that are heavily obscured by line of sight dust. Across the waveband there are a host of spectral lines of key ions, atoms and molecules and characteristic signatures of various types of dust particles. It is therefore possible, for instance, to probe the physics, chemistry and dynamics of interstellar matter (ISM) in the immediate vicinity of galactic nuclei or obscured star forming regions, or investigate the dense and dusty circumstellar shells of young stellar objects and evolved cool stars. With the successful launch and operation of the Infrared Space Observatory (ISO) of the European Space Agency (ESA) a new era has begun in sensitive photometry, imaging and spectroscopy across the entire 2.5 to 200 $\mu$m band. In the following, we will discuss some examples of Galactic and extragalactic spectroscopy that has been undertaken with ISO.

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## 2. What powers (ultra-) luminous infrared galaxies?

One of the key discoveries of the Infrared Astronomical Satellite (IRAS) survey in the mid 80's was the identification of a class of very luminous (L $\sim 10^{11.5-12.5}$ $L_\odot$) galaxies emitting most of their energy in the far-infrared (30 to 300 $\mu$m) wavelength band (e.g. Sanders & Mirabel 1996). Many of them appear to be interacting galaxies, or advanced mergers. They are very gas- and dust-rich with typical gas masses of $\sim 10^{10}$ $M_\odot$ concentrated in the central kiloparsec. A key open question about these infrared luminous galaxies is the source(s) of their luminosity. Based on their far-infrared, millimeter and radio properties many authors have argued that they are powered by active star formation. Their optical properties, on the other hand, resemble narrow line active galactic nuclei. The spectrometers on ISO (SWS: de Graauw et al. 1996a, LWS: Clegg et al. 1996) now allow sensitive mid- and far-infrared observations as a new, very specific tool for investigating the physical processes at the nuclei of obscured galaxies (for details see the special issue of Astronomy and Astrophysics dedicated to ISO: Lutz et al. 1996a,b, Rigopoulou et al. 1996, Sturm et al. 1996, Kunze et al. 1996, Moorwood et al. 1996, Fischer et al. 1996 etc.).

The ionic infrared emission lines toward galactic nuclei arise, like optical emission lines, predominantly from photoionized gas. Hence a powerful tool for investigating whether star formation or a central AGN dominates in obscured nuclei is to study the excitation state of the mid- and far-infrared emission line spectrum. Of particular interest are high excitation ("coronal") lines that require a much harder radiation field than can be delivered by stars, and thus are signposts for a (hidden) AGN. As a demonstration of SWS's capabilities in this regard, Figure 1 shows two full scans of the entire 2.5 $\mu$m to 45 $\mu$m spectrum in the classical starburst galaxy, M82, and in the nearby Seyfert 2 galaxy, Circinus (A1409–65). The qualitative and quantitative differences in the emission line spectra of the two galaxies are obvious. M82 is dominated by fairly low ionization species ([NeII], [SIII], [SiII], [ArII]) while Circinus also shows very intense high excitation lines ([OIV], [NeV], [NeVI], [MgVIII], [SiIX]) with ionization potentials up to 320 eV (see Moorwood et al. 1996 and Oliva et al. 1994 for more details). Both galaxies (and most others we have observed so far) show also a number of $H_2$ rotational emission lines (see below section 3) as well as a host of pronounced emission features arising from UV-heated, very small dust grains and PAHs (3.2 $\mu$m, 6 to 8.6 $\mu$m and 11 to 12.7 $\mu$m: e.g. Verstraete et al. 1996).

Figure 2 is a plot of the (dereddened) [NeV]/[NeII] and [OIV]/[NeII] line ratios (or $3\sigma$ upper limits) for 11 galaxies observed so far with SWS (Lutz et al. 1996a). This includes several starburst and AGN templates, as well as

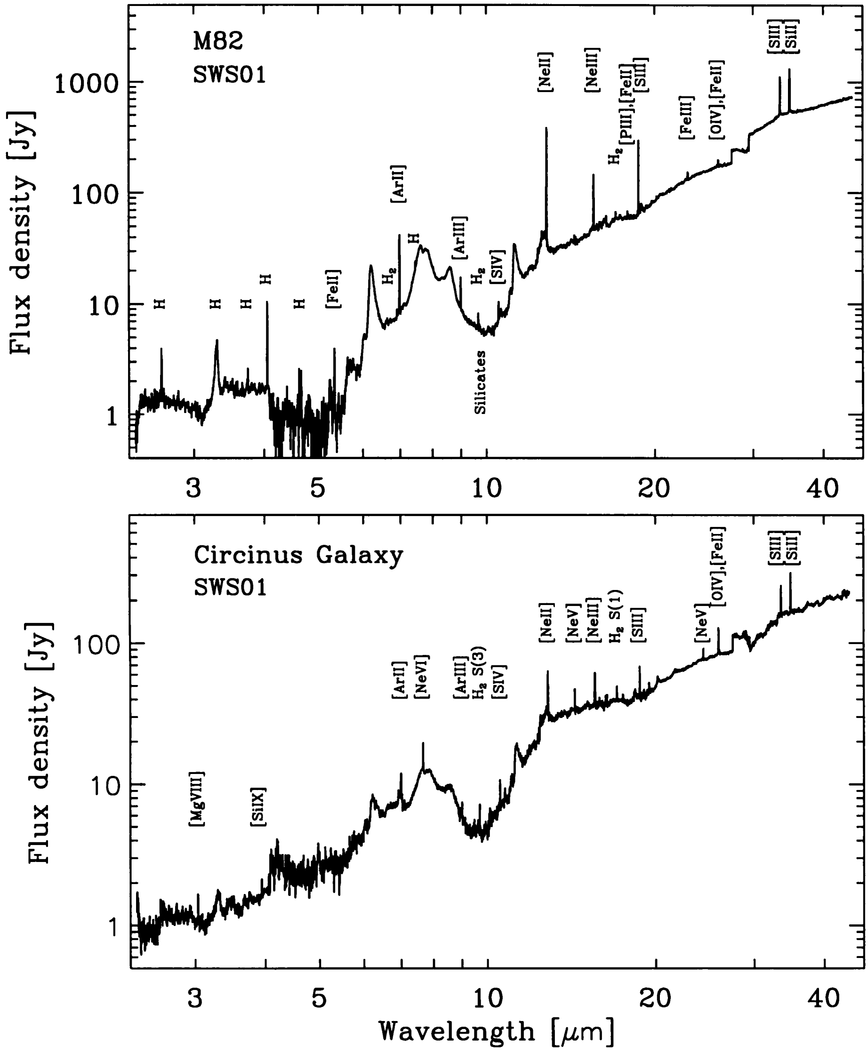

*Figure 1.* Full 2.5-45 $\mu$m SWS spectra of the starburst galaxy M82 (upper panel) and the Seyfert 2/starburst galaxy Circinus (Moorwood et al. 1996). The jumps at $\sim$ 30 $\mu$m are due to a change in aperture.

three typical (ultra-) luminous IRAS galaxies (Arp 220, NGC 6240, NGC 3256). In all sources known to be powered by stars alone, the [NeV]/[NeII] and [OIV]/[NeII] ratios are $\leq 0.1$, while these ratios are between 0.13 and 1.5 in the two AGNs. All three luminous IRAS galaxies also have line ratios

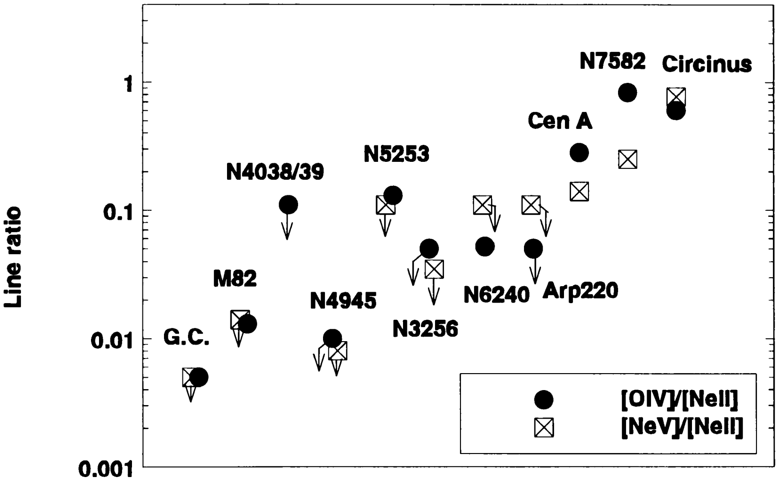

*Figure 2.* Dereddened 14.3 $\mu$m [NeV] (excitation potential 97 eV)/12.8 $\mu$m [NeII] and 25.9 $\mu$m [OIV] (excitation potential 55 eV)/12.8 $\mu$m [NeII] ratios (or $3\sigma$ upper limits) for 11 galaxies observed so far by ISO SWS (Lutz et al. 1996a). To the left are the starburst template galaxies, to the right three active galactic nuclei. The three ultra-luminous IRAS galaxies (NGC 3256, NGC 6240, Arp 220) are in the middle.

$\leq$0.1, strongly supporting the notion that an (even moderately extincted) AGN cannot be the main source of their luminosity. *It is thus very probable that Arp 220, NGC 6240 and NGC 3256 are powered mainly by stars (although one cannot exclude of course that an AGN contributing a fraction of the bolometric luminosity is present).*

Assuming that massive stars dominate the luminosity of Arp 220, NGC 6240 and NGC 3256, what is the evolutionary state of the starburst? Lutz et al. (1996a) have used a star cluster evolution code to calculate the number of stars of different type and the global $L_{Bol}/L_{Lyc}$, $L_K/L_{Lyc}$ and supernova rate to $L_{Bol}$ ratios as a function of time in different star formation histories. Constant star formation models and models with low upper mass cutoffs ($M_{up} \sim 25\ M_\odot$) do not fit any of the objects. From the [NeIII]/[NeII] line ratios and for Kurucz (1992) atmospheres the effective temperatures of the radiation field in the starburst galaxies M82, NGC 4945, NGC 4038/39, NGC 5253, as well as in the luminous IRAS galaxies NGC 3256 and NGC 6240 are at or even above 40000 K, indicating that young, massive O stars are present. $\delta$-bursts fit localized regions fairly well. One particularly interesting case of such a confined, local $\delta$-burst region is the "overlap" region in the "Antennae" galaxy pair (SWS: Kunze et al. 1996, LWS: Fischer et al. 1996, CAM: Vigroux et al. 1996). *The best overall fits for both starburst* *templates and the luminous IR galaxies observed so far are for moderately extended bursts ($\Delta t \sim 1 - 2 \times 10^7$ years) with mean ages ranging between 1 to 7 × $10^7$ years and high upper mass cutoffs (50 to 100 $M_\odot$).* Arp 220 and NGC 6240 still require somewhat older ages than the starburst templates but otherwise are very similar. Spatially resolved near-infrared imaging spectroscopy of M82 (Förster et al. 1996, Satyapal et al. 1995) and NGC 1808 (Krabbe et al. 1994, Kotilainen et al. 1996, Tacconi-Garman et al. 1996) shows that bursts that appear to be extended in time when their integral emission is considered break up at high spatial resolution into a number of local, $\delta$-bursts (~ giant HII regions or massive star clusters) of different ages (see also Rieke et al. 1993).

There still remain substantial uncertainties in these conclusions. First it will obviously be necessary to observe a larger sample of (ultra-) luminous infrared galaxies before one can be sure that the conclusions reached by Lutz et al. are generally applicable and before it is clear how these findings fit into an evolutionary scheme; this is the purpose of guaranteed time observations that will be carried out with ISO in the next year. Second, while the general conclusion that the luminous infrared galaxies discussed here are powered by massive stars is fairly robust, for several reasons the detailed constraints on the starburst properties are still fairly uncertain. Stellar atmosphere models by Sellmaier et al. (1996) predict more energy output in the 20 to 50 eV range than the Kurucz (1992) models used by Lutz et al. and thus require less massive stars for the same [NeIII]/[NeII] etc. ratios. Line fluxes, line ratios and extinction corrections all are subject to ±30% calibration uncertainties and to uncertainties in the extinction curve. Finally, there are the issues of metallicity and the effects of dust within the HII regions which need to be addressed by more detailed future studies with ISO.

## 3. Warm molecular hydrogen in the ISM

ISO also allows now, for the first time, measurements of a wide range of rotational and ro-vibrational lines of the $H_2$ molecule. This includes the lowest ground-state rotational line, S(0) at 28.2 $\mu$m (500 K above ground), as well as $v$=1–0, 2–1 and 3–2 ro-vibrational lines in the 2 to 3 $\mu$m region that come from levels $\geq$ 15000 K above ground. The new observations give interesting information on the amount and excitation mechanisms of warm $H_2$ in different regions. As examples of the emerging results, Figure 3 shows the excitation diagrams (derived upper level column densities divided by their statistical weights) of the observed $H_2$ lines in a Galactic photon dominated region (PDR: S140 from Timmermann et al. 1996) and a shocked cloud in a region of star formation/Herbig Haro object (Cep A: Wright et al. 1996). In excitation diagrams an isothermal level population lies on a straight line with a slope inversely proportional to temperature. It is thus clear from Figure 3 that simple isothermal models (such as single temperature, high density PDRs or single C-shocks) do not fit the data.

For S140, the very flat (~ high excitation temperature) distribution of the excitation diagram for upper level energies above ~ 5000 K indicates that the higher levels are mainly populated by UV pumping and cascading, while the lower rotational states are thermalized by collisions. This behavior has been predicted theoretically as a generic characteristic of PDRs (e.g. Sternberg & Dalgarno 1989, Burton 1992) although the new ISO measurements show some significant departures in detail from the published models. For example, Timmermann et al. (1996) find that the data are reasonably well fit by a moderate density ($n(H_2) \sim 10^4$ $cm^{-3}$) and UV field, but very warm, PDR-model.

The excitation diagram of the shocked region in CepA is clearly different from S140. The $v$=0 rotational ladder is at higher excitation temperature than in the PDR S140 (700 K compared to 500 K) while the highest excited ro-vibrational states are at lower excitation temperature (~ 2000 K compared to $\geq$ 10000 K). This behavior is indicative of a cooling layer(s) in shocks. The data fit continuous (C-) shocks qualitatively but no single velocity C-shock model fits the ISO data quantitatively. Wright et al. instead conclude that a good fit to the data requires either a superposition in the ~ 20″ ISO beam of at least two C-shocks with different pre-shock densities, shock velocities and beam filling factors, or, perhaps bow-shock models which naturally create different effective shock speeds in different parts of the shock structure.

We have mentioned already in the last section that rotational $H_2$ lines are now also commonly seen in external galaxies (e.g. Egami et al. 1996, Kunze et al. 1996, Rigopoulou et al. 1996, Sturm et al. 1996, Valentijn et al. 1996). Egami et al. (1996) have analyzed the SWS $H_2$ observations on several galaxies. From observations of the $v$=0–0 S(0), S(1) up to S(7) lines they find excitation temperatures ranging from 150 to 1000 K. A few percent up to several tens of percent of the molecular ISM sampled by millimeter-molecular lines (e.g., CO) is sampled by the warm $H_2$. There is also an indication of a yet cooler component (containing more mass) from the S(0) line.

## 4. $H_2O$, OH, CO and $CO_2$

One of the key goals of infrared spectroscopy with ISO is the measurement of species that cannot be observed from the ground (either in the infrared,

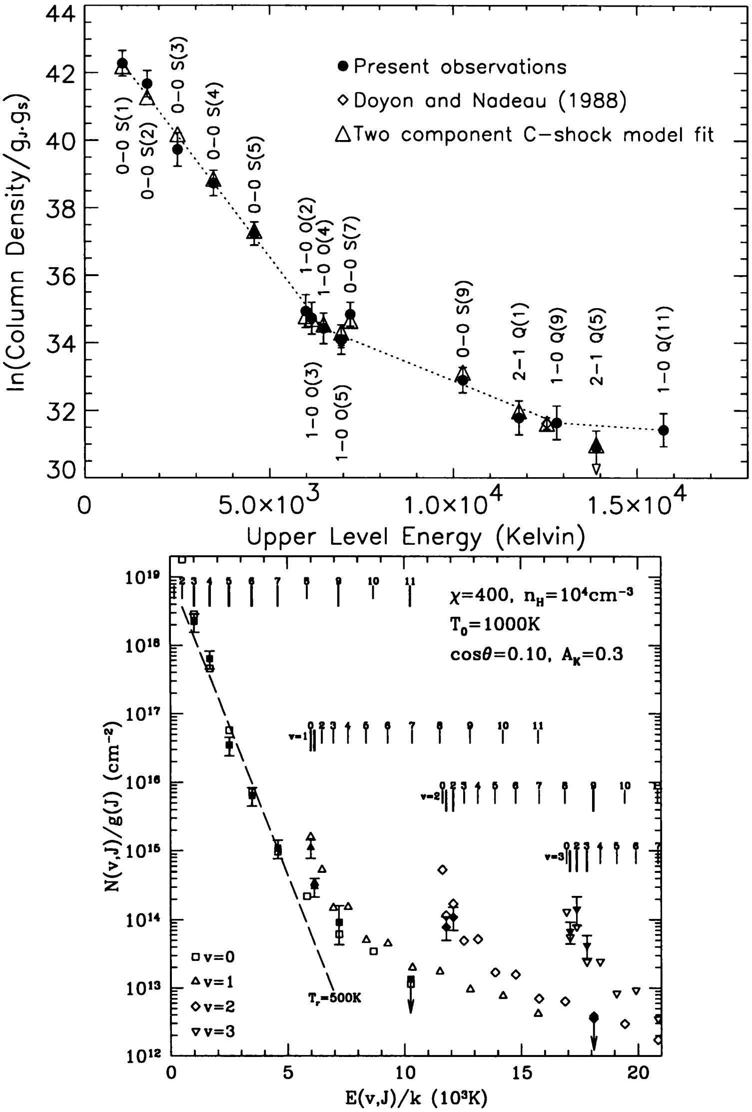

*Figure 3.* SWS observations of $H_2$ emission lines in Galactic sources. Upper: Logarithm of upper level column density as a function of upper level energy (excitation diagram) for GGD 37 in Cep A (from Wright et al. 1996). The various detected rotational (0–0) and ro-vibrational transitions are labeled and dashed lines are plotted to guide the eye to the different excitation temperature regimes (700 to $\geq$10000 K) in the plot. The model parameters are pre-shock density $n(H_2)=10^4$ cm$^{-3}$ and $10^{6.5}$ cm$^{-3}$, shock velocity $v_s$=20 km s$^{-1}$ and 35 km s$^{-1}$, and covering factor $\Phi$=0.5 and 0.001 for the first and second C-shock respectively. Lower: $H_2$ excitation diagram for the photon dominated region S140 (from Timmermann et al. 1996). Observed lines are given as filled symbols and model points are open symbols. Model parameters are listed in the upper right.

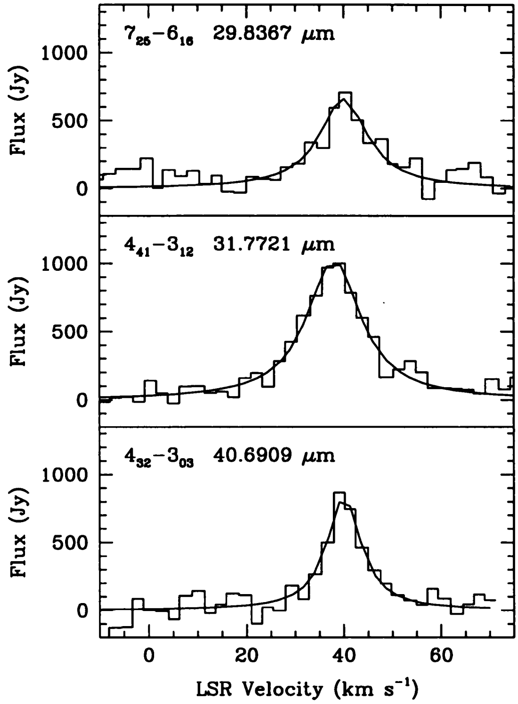

*Figure 4.* Continuum subtracted SWS Fabry-Perot spectra (resolving power ~ 30000) of three rotational $H_2O$ lines in W Hya (Neufeld et al. 1996).

radio or submm/mm band). One such key measurement is the study of water vapor in interstellar and circumstellar clouds. Both ISO spectrometers already have succeeded in detecting $H_2O$ lines in several environments. For details we refer to Helmich et al. (1996), van Dishoeck & Helmich (1996) and van Dishoeck et al. (1996), Cox et al. (1996), Neufeld et al. (1996), Justtanont et al. (1996) and Liseau et al. (1996). As examples of these first results, Figures 4 and 5 show the first detections of several $H_2O$ rotational emission lines (with the SWS Fabry-Perot at a resolving power ~ 30000) in the outflowing envelope of the luminous late type star W Hya (Neufeld et al. 1996) and of the 6.2 μm $\nu_2$ ro-vibrational band in absorption against several young stellar objects (van Dishoeck & Helmich 1996).

In the case of W Hya (Fig. 4), Neufeld et al. deduce that the mass outflow rate is $\sim 10^{-5}$ $M_\odot$ yr$^{-1}$ which is one to two orders of magnitude greater than had been deduced previously from mm-lines. For AFGL 2591 (Helmich et al. 1996), AFGL 2136 and AFGL 4176 (van Dishoeck & Helmich 1996,

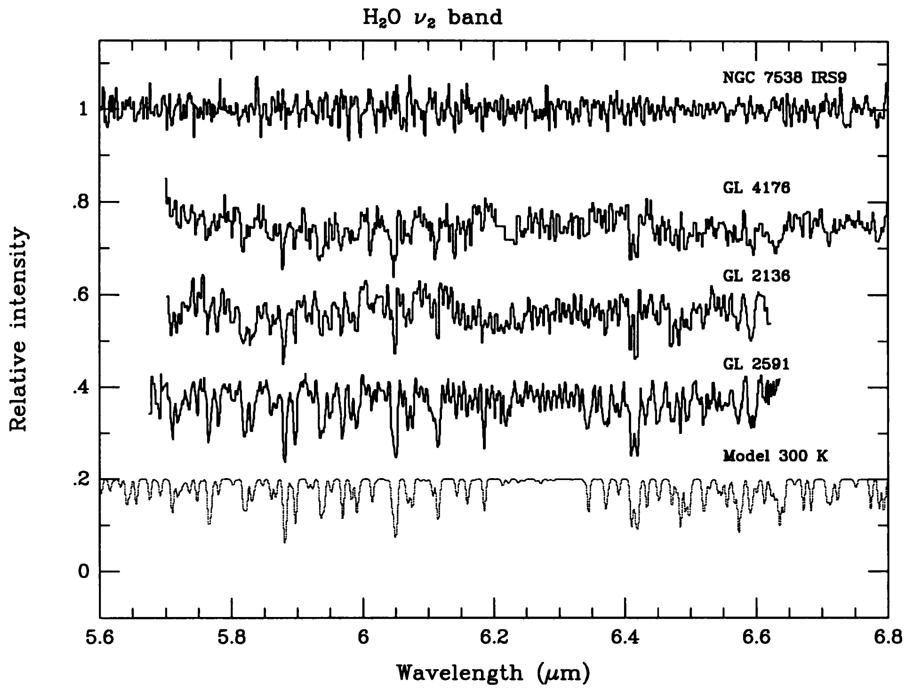

*Figure 5.* Normalized SWS spectra of the $\nu_2$ 6.2 $\mu$m $H_2O$ band in NGC 7538 IRS 9, AFGL 4176, AFGL 2136 and AFGL 2591, shifted by 0.0, –0.2, –0.4 and –0.6. A model spectrum for a column density $2\times10^{18}$ cm$^{-2}$, temperature 300 K and velocity width b=5 km s$^{-1}$ is shown for comparison (from van Dishoeck & Helmich 1996).

Fig. 5) it is concluded that the $H_2O$ infrared absorption comes from warm gas (200 to 1000 K) that originates in "hot cores" in the immediate environment of the newly-formed stars. In all three sources the deduced abundance of $H_2O$ relative to $H_2$ is estimated to be a few $\times$ $10^{-5}$, significantly greater than in cool molecular clouds. Presumably this relatively high abundance can be explained by the thermal heating and evaporation of grain mantles exposed to the infrared radiation of the young stars, and/or by high temperature, gas phase reactions that can proceed in the warm star-forming regions.

Other highlights include measurement of the 4.6 $\mu$m CO ro-vibrational bands in absorption in a number of objects/line of sights (the late type star NML Cyg: Justtanont et al., young stellar objects: van Dishoeck et al., Galactic Center: Lutz et al 1996b). From comparison to the nearby $CO_2$ ro-vibrational band both van Dishoeck et al. and Justtanont et al. find that the gas phase abundance of $CO_2$ is a percent or less of that of CO. Most of the interstellar $CO_2$ appears to be in the solid state ($CO_2$ ice: de Graauw et al. 1996b).

OH absorption has been observed in ro-vibrational lines toward the star NML Cyg (Justtanont et al. 1996), as well as in the 34 $\mu$m $^2\Pi_{3/2}$ J=3/2 – $^2\Pi_{1/2}$ J=5/2 transition toward NML Cyg (Justtanont et al.), the Galactic Center (Lutz et al. 1996b) and the ultra-luminous infrared galaxy Arp 220 (Sturm et al. 1996).

This summary obviously can all but give a first glimpse of the spectroscopic measurements that can now be made. Yet it is already apparent that infrared spectroscopy with ISO will contribute important information on a number of very interesting questions in modern astrophysics and astrochemistry.

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3
HCN and HCO+ Images of the PDR in the Orion Bar
4
OI(63μm) and CII(158μm) Observations of PDRs in Reflection Nebulae