

THE FAR-IR SPECTRUM OF IRC+10216

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ABSTRACT

We present an ISO¹ Long Wavelength Spectrometer (LWS) grating spectrum of the carbon-rich circumstellar envelope -CSE- of IRC+10216 between 43 and 197 μm . The spectrum consists of strong dust emission plus a forest of emission lines from CO, HCN, H¹³CN and vibrationally excited HCN ($\nu_2=1^1, 2^{0,2}$ and $\nu_{1,3}=1$). All the CO lines between $J=14 \rightarrow 13$ and $J=39 \rightarrow 38$ have been detected while lines of HCN with J_u as high as 48 have also been observed. The molecular emission arises from the warm and dense gas located in the innermost zone of the CSE. The CO and HCN emission can be easily explained if the vibrational and rotational temperatures are around 700-1500 K.

We also report the detection of two ro-vibrational lines of the bending mode of the C₃ molecule around 62 cm^{-1} (157.2 μm) through the observation of IRC+10216 with the Fabry-Perot spectrometer of the LWS.

INTRODUCTION

IRC+10216 is the brightest C-rich evolved object in the sky. It has an extended envelope where more than 30 molecular species have been detected and it is probably one of the best studied objects at all wavelengths. This object has a particularly rich carbon chemistry and most of the species detected in its molecular envelope are carbon chains radicals (C₃H: Cernicharo *et al.* 1986a,b, 1987a; C₆H: Guélin *et al.* 1987a, Cernicharo *et al.* 1987b; C₇H: Guélin *et al.* 1997, C₈H: Cernicharo & Guélin 1996; H₂C₃ and H₂C₄: Cernicharo *et al.* 1991a,b) which are formed in

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the external layers of the molecular envelope (Guélin, Lucas and Cernicharo 1993). Some of the detected species are metal-bearing molecules as the metal halides NaCl, AlCl, AlF, KCl, first detected in this envelope by Cernicharo and Guélin (1987). The spatial distribution of these molecules peaks on the central. However, Guélin, Lucas and Cernicharo (1993) have shown that some metal-bearing molecules, such as MgNC, are mostly in the external layers of the circumstellar envelope.

The innermost regions of the envelope are dominated by a chemistry at thermodynamical equilibrium (Tsuji, 1973). Most of the stable diatomic and triatomic species form there efficiently (CO, HCN, C₂H₂, SiO, CS, SiS, ...). The most abundant of these molecules are observed at radio wavelengths, but most species are too weak to be detected. They could nevertheless be detected in absorption against the strong IR flux of the central source. Hence, the molecular envelope of IRC+10216 constitutes an interesting 'laboratory' for the study of the circum- and interstellar chemical processes; it is also the best evolved star for near-, mid- and far infrared studies. ISO observations of IRC+10216 with the SWS and LWS spectrometers will allow to identify new molecular species, some of them playing an important role in the chemistry of these objects. Molecules like CO₂, CS₂, NCCN, CH₃, CH₄, ... could be detected in the SWS and LWS spectral scans. Among the expected new molecules it is worth to mention the N-atomic carbons C₄, C₆, C₇, which are efficiently formed in the external layers of the circumstellar envelope (Cherchneff and Glassgold, 1993).

This contribution presents a grating spectrum of IRC+10216 between 43 and 197 μm (Cernicharo *et al.* 1996) obtained with the LWS spectrometer. The LWS has been described by Clegg *et al.* (1996).

WHAT TYPE OF TRANSITIONS COULD BE EXPECTED IN THE FAR-IR SPECTRUM OF IRC+10216 ?

While the abundance of the long and polar carbon chains have been derived the ISM and the CSM, the light molecules necessary to the formation and synthesis of such chains have not yet been detected, mainly due to their lack of permanent dipole moment and hence of pure rotational transitions. Molecules without dipole moment can be observed, however, in the infrared through their vibrational transitions. Most molecular species in IRC+10216 have been detected at radio wavelengths through the observations of its pure rotational spectrum. Cyanopolyynes as long as HC₇N, HC₉N and HC₁₁N are abundant molecules in sources like TMC1 and IRC+10216 and long carbon chain radicals have been detected in the same sources through their pure rotational spectrum at radio wavelength. The relatively slow decrease in the abundance of the higher order chains (Cernicharo *et al* 1987b) implies a very efficient production mechanism. Yet, only a few of these long and polar carbon chains have been observed in the CSM. Important non-polar molecules, such as C₄H₂, C₆H₂, C₄, C₅, ..., and other species with small permanent dipole moments have so far escaped detection.

In comparison with the millimeter/submillimeter domains where up to now most of the studies have been made, the far-IR range provides, together with near-IR high resolution spectroscopy, a unique opportunity to probe the inner hottest regions of the CSE. The molecular transitions at IR wavelengths involve high quantum numbers and it becomes possible to trace the molecular material in the innermost zones of the CSE. Obviously, the pure rotational spectrum of long molecular chains like C₂H, C₄H, ..., are not detected because the quantum numbers associated to the transitions in the far-IR domain are very high, and the corresponding rotational levels are not populated. However, some exotic polyatomic molecules could have vibrational modes very low in energy (the bending modes for example) which will produce transitions in the far-infrared. C₄H is a molecular species for which rotational emission from the $v_7=1, 2$ vibrational levels have been found (Guélin *et al* 1987b). Although the ro-vibrational transitions of the v_7 bending mode are expected around 100 μm , the exact frequencies are unknown and hence it is difficult to find the expected emission (or) absorption in the LWS spectrum. The pure rotational transitions of light molecules, and those of very abundant species like CO, HCN, CCH, HNC, ..., could cover the full far-IR range (if the excitation mechanisms, collisions and IR photons, allow an efficient pumping of their rotational levels).

THE LWS SPECTRUM OF IRC+10216

Cernicharo *et al* (1996) have observed the 43-197 μm spectrum of IRC+10216 as observed with the LWS spectrometer on board of the ISO satellite. Figure 1 shows the continuum subtracted LWS spectrum of IRC+10216 together with the results of a LVG model for CO and HCN (Cernicharo *et al* 1996). The spectrum is dominated by the emission of carbon monoxide and HCN in all their vibrational states. Some lines of ¹³CO and H¹³CN are also detected.

Twenty six CO pure rotational lines have been detected in IRC+10216, from J=14→13 up to J=39→38. The CO lines are strong throughout the wavelength range of the LWS and only show a drop in the intensity levels for the highest J rotational transitions. Besides the rotational lines of CO, a forest of HCN lines from different vibrational states were detected from J=18→17 to 48→47. The HCN lines from the ground state are always accompanied by a strong line at shorter wavelengths through the full LWS range (see Figure 1). The spacing between these lines and their frequency ratios are similar to those of HCN. Hence, the rotational constants, the mass, and the structure of the carrier of these lines must be very similar to that of HCN. After elimination of a few obvious species for which the frequencies are well known, Cernicharo *et al* (1996) concluded that the best candidate was HCN itself, but in bending vibrational excited states. HCN has a bending mode, v_2 , at $\approx 713 \text{ cm}^{-1}$, and two stretching modes v_1 and v_3 , at 2096 and 3311 cm^{-1} respectively. Cernicharo *et al* (1996) concluded that after removing the CO lines, all the remaining strong features in the far-IR spectrum of IRC+10216 are due to HCN. The blue feature appearing near the HCN lines corresponds to the $v_2=1 \text{ l}=1^{\circ}$ component, while the $\text{l}=1^{\text{d}}$ is blended with HCN itself.

Some of the weak features remaining in the far-IR spectrum of IRC+10216 could be assigned to rotational transitions of CS and SiO. However, the limited spectral resolution of the data in Figure 1 avoids any certain identification for these features. Cernicharo (1996) searched for NaH, MgH, CaH, NH, CH, FeH, NiH, SH, SiH, CH₂, and other light molecular species without success. However, they reported a tentative detection of the Q(2,4,6,8) lines of the bending mode of triatomic carbon, C₃, around 157.2 μm (see below).

The most spectacular result from the ISO/LWS spectrum of IRC+10216 is the forest of lines arising from the different vibrational levels of HCN. This result could have been expected in view of the strong maser emission found by Lucas and Cernicharo (1989) in the $v_2=1$ state and the strong thermal emission in the J=2-1 and J=3-2 lines from the other vibrational levels of

HCN. For a gas thermalized at 1000 K, 19% and 15% of the HCN molecules will be in the $v_2=1^1$ and in the $v_2=2^{0,2}$ levels respectively. At 1500 K the v_1 level will contain 5% of the HCN molecules and, together with the v_3 level, could start to contribute to the forest of HCN lines in IRC+10216. The typical shape of the

HCN lines, after convolution with the grating response, corresponds to a double peaked line ($v_2=0, 1, 2$) with a red shoulder arising from the rotational lines in excited stretching modes and a weak blue shoulder from the bending levels $v_2=3,4$.

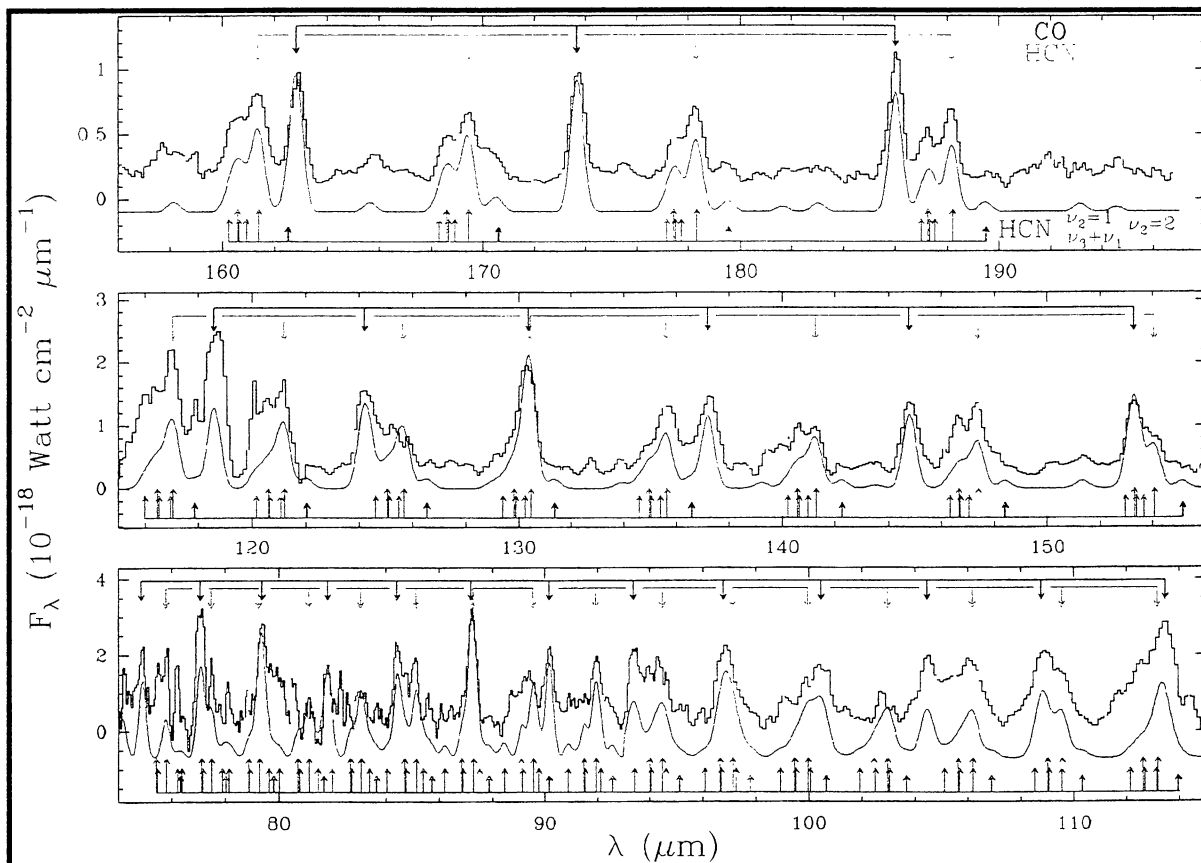


FIGURE 1: Continuum subtracted LWS grating spectrum of IRC+10216 from 75 to 197 μm (thick line). An offset has been introduced to the continuum to show simultaneously the computed emission of the CO $v=0, 1$, $^{13}\text{CO } v=0, 1$, HCN and $\text{H}^{13}\text{CN } v=0$, and HCN $v_2=1,2$ $v_{1,3}=1$ (thin line) -see Cernicharo et al 1996 for details. The rotational transitions of CO, HCN, and HCN $v_2=1,2$ and $v_{1,3}=1$ are indicated at the top and bottom of each panel. The weak lines in the model correspond to H^{13}CN , ^{13}CO and to the stretching modes of HCN (from Cernicharo *et al.* 1996).

THE ROLE OF HCN IN EVOLVED CARBON-RICH STARS

Cernicharo et al (1996) have computed the line intensities of HCN and CO through LVG models for their ground state. The best agreement between the observations and the model results (which are shown in Figure 1) is obtained for $\text{HCN}/\text{CO}=0.1$ which corresponds to an HCN abundance of $3\sim 10^{-5}$, a value that agrees with that derived from millimeter observations (Cernicharo et al 1987). Several lines of

H^{13}CN are detected corresponding to the rotational transitions $J=18\rightarrow 17, 19\rightarrow 18, 21\rightarrow 20, 22\rightarrow 21, 23\rightarrow 22$ and $26\rightarrow 25$. Some weak and broad features present in Figure 1 could also correspond to the $v_2=1,2$ levels of H^{13}CN . Taking into account the uncertainties associated with the data calibration and with the baseline used to remove the continuum, the agreement between the observations and our model results is reasonably good. In the far-IR, $\lambda > 70 \mu\text{m}$, the power emitted in the HCN lines is $0.44 L_{\odot}$ while that of CO is $0.28 L_{\odot}$ (even when the millimeter and sub-millimeter

lines of CO and HCN are included). Hence HCN is the main coolant of this C-rich CSE where it plays a similar role to that of water in O-rich CSEs.

TRIATOMIC CARBON

Among the carbon chain radicals, triatomic carbon has played an important role in astrophysics since its detection in cometary tails in the last century and its posterior identification in the laboratory by Douglas in 1951. Its spectroscopic constants were derived by Herzberg and coworkers in 1965 (Gausset et al, 1965). There is some low-resolution evidence for the appearance of the optical bands of C_3 in the atmospheres of cool stars (see, e.g., Zuckerman et al 1976), and it has been definitely identified in the envelope of IRC+10216 through its ν_3 antisymmetric stretching band by Hinkle et al (1988). They derived an abundance for C_3 of 10^{-6} . The ν_2 bending mode at 62 cm^{-1} (90 K) is the only way to detect this molecule in the ISM because the flux of molecular clouds at the frequency of the stretching mode of C_3 is too low to allow systematic searches of C_3 or other polyatomic species.

Cernicharo et al (1996) have reported a tentative detection of the bending mode of triatomic carbon in IRC+10216. Figure 1 shows that around $158\ \mu\text{m}$ there is a broad feature which coincides in λ with the lowest J lines of the Q-band of C_3 . However, these observations lack of spectral resolution to provide a definite assignment.

Cernicharo *et al.* (1997) have detected the R(2) and R(4) lines of triatomic carbon observed with a spectral resolution ≈ 10000 . The broad feature in the grating spectrum that was assigned by Cernicharo et al to the Q band of triatomic carbon contains the Q(2), Q(4), Q(6), Q(8) and the R(0) lines. Many other lines from the P and R bands could also be marginally depicted in the grating spectrum but baseline effects and the limited resolution do not permit to derive line intensities and convincing identifications. However, the detection of the R(2) and R(4) lines definitively confirm the presence of the $(0,1^1,0) \rightarrow (0,0,0)$ ro-vibrational lines of C_3 .

Only light species could have rotational transitions in the far-IR domain. The pure rotational transitions of the heaviest species involve high quantum numbers and, hence, very high energies. Polyatomic species, like C_3 , C_4 , C_5 , C_4H_2 , C_6H_2 , ... have, however, vibrational bending modes at very low energy. The Q bands of these modes will contain absorption/emission from many lines and could contribute, like the case of IRC+10216, to the far-infrared spectrum of bright infrared sources (ISM and/or CSM).

A high resolution and sensitive spectral survey of IRC+10216 with the HET receiver for FIRST will permit to study in detail the contribution of light species, and of the low energy bending modes of polyatomic molecules, to the emission of IRC+10216. The strong lines from HCN (ground and vibrational states) and CO could allow, when observed with high velocity resolution, to study in detail the innermost region of the envelope.

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