Astron. Astrophys. 363, L9–L12 (2000)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

Astronomical detection of the free radical SiCN

M. Guélin[1], S. Muller[1], J. Cernicharo[2], A. J. Apponi[3], M .C. McCarthy[3], C.A. Gottlieb[3], and P. Thaddeus[3]

[1] IRAM, 300 rue de la piscine, 38406 S$^{\rm t}$ Martin d'Hères, France (guelin@iram.fr)
[2] Instituto de Estructura de la Materia, C/Serrano 121, 28006 Madrid, Spain
[3] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

Received 15 September 2000 / Accepted 12 October 2000

Abstract. We report the detection of the SiCN radical in an astronomical source, the envelope of the C star IRC +10216/CW Leo. The microwave spectrum of SiCN was recently studied by four of us in the laboratory and the rotational transition frequencies were accurately measured. The ground fine structure state, $^2\Pi_{1/2}$, has three rotational transitions, each with λ-doubling in the 80–116 GHz atmospheric window ($J = 7.5 \rightarrow 6.5$, $8.5 \rightarrow 7.5$ and $9.5 \rightarrow 8.5$, at 83.0, 94.0, and 105.1 GHz). The three λ-doublets (six components) are detected at a level of 5 mK with the IRAM 30-m telescope. Judging from the cusped shape of the line profiles, SiCN is largely confined to the outer molecular envelope, like most other radicals. Its abundance relative to H_2 is estimated to be 4×10^{-9}, a factor of 20 lower than that of MgNC.

The isoelectronic radical SiCCH was not detected. We confirm our previous tentative detections of the carbon chain H_2C_6 and of NP in IRC+10216.

Key words: molecular data – stars: circumstellar matter – stars: AGB and post-AGB – ISM: molecules – radio lines: stars

1. Introduction

The envelope expelled by the carbon star CW Leo/IRC +10216 is remarkably rich in reactive species and in refractory compounds. Most of the stable metal-bearing molecules are observed fairly close the star. The reactive species, in particular the linear carbon-chain radicals, are generally confined to a thin shell in the outer envelope. Whereas the stable metal compounds form in the hot stellar atmosphere before being expelled in the envelope, the C-chains must be formed in situ in the cold, rather tenuous circumstellar medium.

Previous to the work here, only four metal-containing radicals have been identified in IRC +10216: SiC, SiN, MgNC and MgCN. Interferometric maps of the fairly strong mm-wave emission of SiC and MgNC indicate that these radicals exist in the same outer shell as the carbon chains. This somewhat unexpected finding may be important to understand the interaction of metals with grains and the depletion of metals in the gas ejected by objects like IRC +10216 into the interstellar medium (see e.g. Guélin et al. 1993, Turner 1994, Glassgold 1996). For this reason, detection of more metal-containing radicals is clearly of interest.

The small number of metallic radicals observed in space is largely due to the lack of accurate spectroscopic data. Recently, four of us succeeded in detecting in a laboratory discharge three silicon-bearing radicals of astrophysical interest: SiCCH, SiCN and SiNC (Apponi et al. 2000, hereafter AMGT). The microwave spectra of the ground states of these radicals are now accurately measured, which prom-pted us to search for the first two species in space. In this Letter, we report the discovery of SiCN in IRC +10216.

2. Observations

The three just mentioned silicon radicals are linear and have a regular $^2\Pi$ electronic ground state. In either case, their rotational spectra consist of nearly harmonic Λ doublets separated by $\sim$ 12 GHz. Each rotational transition is split into several components by Λ-doubling and magnetic hyperfine structure, but for the large J transitions of interest here, the hyperfine structure is unresolved, and the spectrum reduces to a series of doublets with a constant splitting. The two Λ-doublet components are denoted e and f (see AMGT). By analogy with MgNC and HC_3N, which have similar moments of inertia and dipole moments[1], the rotational lines are expected to peak in intensity in IRC +10216 near a wavelength of 3 mm.

The observations were made with the IRAM 30-m telescope in July 2000. Two SIS mixer receivers with orthogonal polarizations were used to observe the 3-mm rotational transitions of SiCN and SiCCH. The receivers were tuned to a single sideband, with rejections of the upper sideband > 25 dB. (The rejection level was measured against a frequency-modulated load and checked by recording the intensity of strong astronomical lines

Send offprint requests to: M. Guélin

[1] The permanent dipole moments of SiCCH, SiCN, and SiNC are μ_0= 1.4 D, 2.9 D and 2.0 D, respectively, according to ab initio calculations – see references in AMGT

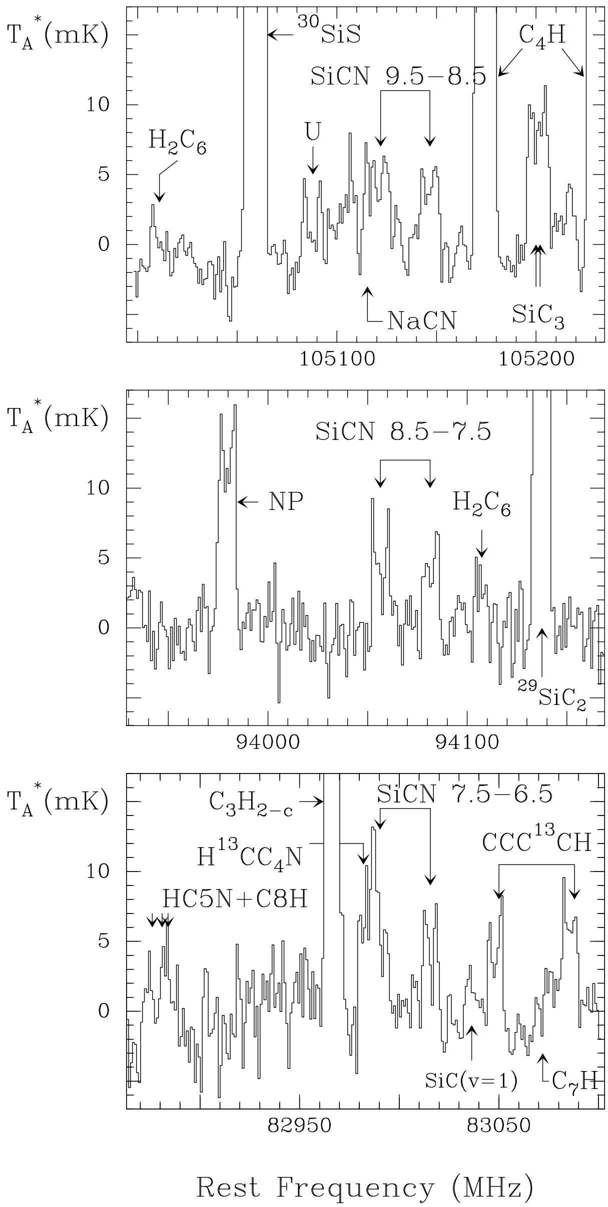

Fig. 1. Spectra from the 30-m telescope of three successive rotational transitions of SiCN. The position of the SiCN Λ-doublet components, at the center of each spectrum, and those of other identified lines are indicated by arrows. The lines of C_4H at 105174 MHz and 105231 MHz are the fine-structure components of the $N = 11 \rightarrow 10$ rotational transition in the $\nu_7 = 2$, $l = 0$ bending state. The broad feature around 82880 MHz is a blend of transitions of C_8H and of vibrationnally excited HC_5N (ν_{11}=2); note that the noise is larger on the left side of the bottom spectrum, because the integration time was a factor of 3 smaller below 82960 MHz, than above.

from the image sideband.) The system noise temperature was 110-150 K.

The data were taken in the balanced wobbler-switching mode, with a wobbling period of 0.5 Hz and a throw of 2'. This mode yielded baselines so flat that only first degree polynomials had to be removed across the 0.5 GHz-wide band of the spectrometer. The channel resolution was 1 MHz. The telescope pointing and focus were checked every 1–2 hours on the nearby continuum source OJ287. After calibration and baseline removal, the spectra observed in July 2000 were averaged with spectra previously taken in the course of a spectral survey of IRC +10216 (Cernicharo, Guélin & Kahane 2000, hereafter CGK).

Table 1. Observed line parameters

Obs. freq. MHz	Obs.-Cal. MHz	Species	Transition	$\int T_A^* dv$ mK.kms^{-1}
82990.8^b (4)	.33	SiCN	$7.5 \rightarrow 6.5(e)$	160 (40)
83015.7 (1)	.1	SiCN	$7.5 \rightarrow 6.5(f)$	152 (20)
94056.6 (1)	.2	SiCN	$8.5 \rightarrow 7.5(e)$	159 (23)
94081.7 (3)	.3	SiCN	$8.5 \rightarrow 7.5(f)$	127 (23)
105121.7^b (3)	-.3	SiCN	$9.5 \rightarrow 8.5(e)$	128 (30)
105146.8 (2)	.1	SiCN	$9.5 \rightarrow 8.5(f)$	140 (15)
82983.3^b (3)	-.1	$H^{13}CC_4N$	$32 \rightarrow 31$	240 (40)
83048.4 (3)	.0	$C_3^{13}CH$	$9 \rightarrow 8$	170 (20)
83085.7 (3)	-.1	$C_3^{13}CH$	$9 \rightarrow 8$	195 (20)
93979.8 (1)	-.0	NP	$2.0 \rightarrow 1.0$	370 (20)
94137.3 (1)	-.1	$^{29}SiC_2$	$4_{22} \rightarrow 3_{21}$	1110 (20)
105011.1 (3)	-.3	H_2C_6	$39_{1.38} \rightarrow 38_{1,37}$	63 (15)
105059.2 (1)	.1	^{30}SiS	$6.0 \rightarrow 5.0$	4750 (25)
105174.6 (1)	.3	C_4H	$N = 11 \rightarrow 10$ $(\nu_7 = 2, l = 0)$	2330 (20)
105231.3 (1)	.0	C_4H	$N = 11 \rightarrow 10$ $(\nu_7 = 2, l = 0)$	2340 (20)
Calc. freq. (MHz)	**Obs.-Calc. (MHz)**	**Species**	**Transitions**	**$\int T_A^* dv$ mK.kms^{-1}**
103067.4	–	SiCCH	$9.5 \rightarrow 8.5(e)$	< 38
103098.4	–	SiCCH	$9.5 \rightarrow 8.5(f)$	< 38

The number in parenthesis are 1σ uncertainties on the last digit, derived from least square fits; they do not include the 5% calibration uncertainty. The limits quoted for the SiCCH line intensities correspond to 3σ. ^{b} denotes a partly blended line.

3. Results

Three spectra, corresponding to the $J = 7.5 \rightarrow 6.5, 8.5 \rightarrow 7.5$ and $9.5 \rightarrow 8.5$ rotational transitions of SiCN are presented in Fig. 1. All three doublets are detected, even though two components ($J = 7.5 \rightarrow 6.5\,(e)$ at 82990.4 MHz, and $J = 7.5 \rightarrow 6.5\,(e)$ at 105122.0 MHz), appear partly blended with lines of NaCN and $H^{13}CC_4N$.

Despite the large number of lines observed in IRC +10216 at the 5 mK level, there can be little doubt that the three doublets of Fig. 1 are from SiCN: the rest frequencies of the components are accurately measured; they agree with the laboratory-derived frequencies to within 0.3 MHz, or 1/30$^{\text{th}}$ of the linewidth in IRC +10216 (Table 1). Moreover, we have unsuccessfully searched for alternate assignments of these lines in the standard catalogs of molecular transitions of astrophysical interest, as well as in a line catalog specifically designed for IRC +10216 (see CGK). We note in this respect that we could identify with the help of this catalog all but one of the 18 spectral lines in Fig. 1 not from SiCN.

Among these, we note the $J = 2 \rightarrow 1$ line of NP, at 93979 MHz, the $J_{K-1} = 9_4 \rightarrow 8_4$ lines of SiC_3, at 105200 MHz and 105202 MHz, the $J_{K_{-1}} = 39_1 \rightarrow 38_1$ lines of H_2C_6 at 105011 MHz, and a weak feature which could be a blend of the $J = 35 \rightarrow 34$ $K_{-1} = 3, 2, 0$ lines of H_2C_6 at 94115-120-124 MHz.

SiC_3 is a highly polar rhomboidal molecule which was recently discovered in IRC +10216 by Apponi et al. (1999 – see also CGK). The detection of three rotational lines of NP in IRC +10216 was previously described by CGK. The NP line shown in Fig. 1 is now observed with a better signal-to-noise ratio than before and its frequency (Table 1) and profile shape (Fig. 2c) can be accurately derived. The rest frequency agrees very well with the laboratory-derived frequency, leaving little doubt as to the identification of this phosphorus molecule.

In a previous paper (Guélin et al. 1997), we had reported the tentative discovery of H_2C_6 in IRC +10216. The weak features in Fig. 1 are the fourth and, possibly, fifth spectral lines we assign to this long carbene, confirming our earlier discovery. The detection of H_2C_6 in another astronomical source, TMC 1, was also reported by Langer et al. (1997), shortly after our first report.
Another astronomical source where Si-bearing molecules are detected is Sgr B2. We searched unsuccessfully for the 94.1 GHz lines of SiCN in this source. For an assumed rotation temperature of 20 K, the 3σ limit on the column density we derive is 2×10^{13} cm^{-2}.

4. Discussion

Fig. 2a shows the SiCN line profile obtained by averaging the 4 non-blended components of Fig. 1. The profile has the same cusped shape than the line profiles of the carbon chain molecules and radicals (see e.g. the C_4H line on Fig. 2b). In the case of a spherical envelope expanding with a constant velocity, cusped line profiles are characteristic of optically thin lines arising from a resolved hollow shell. The emission in the horns arises from the blueshifted and redshifted polar caps and the emission at the center of the line from the meridian ring perpendicular to the line of sight. If the shell thickness is constant, the horn-to-center intensity ratio depends primarily on the shell diameter relative to the telescope beam: the larger the shell, the larger the ratio.

The millimeter line emission from the ground and the first vibrationally excited states of C_4H have been mapped with the IRAM interferometer (see e.g. Guélin et al. 1993). They are found to arise from a $4''$ thick shell of radius $15''$. This shell is also the source of emission of the carbon chain molecules and of the MgNC radical, all of which show cusped line profiles, when observed with the 30-m telescope. In contrast, the optically thin ^{30}SiS line (Fig. 2d) which arises from a compact region close to the central star, is flat-topped.

The C_4H line in Fig. 2 arises from the $\nu_7 = 2, l = 0$ bending state, which lies in energy 260 cm^{-1} above the ground state (Yamamoto et al. 1987); the SiCN line arises from the ground vibrational state. The conditions for the excitation of these two lines are quite different. The similarity of their line profiles cannot be a mere excitation effect. It rather implies that both species coexist spatially, and that SiCN is confined in the same thin shell as C_4H.

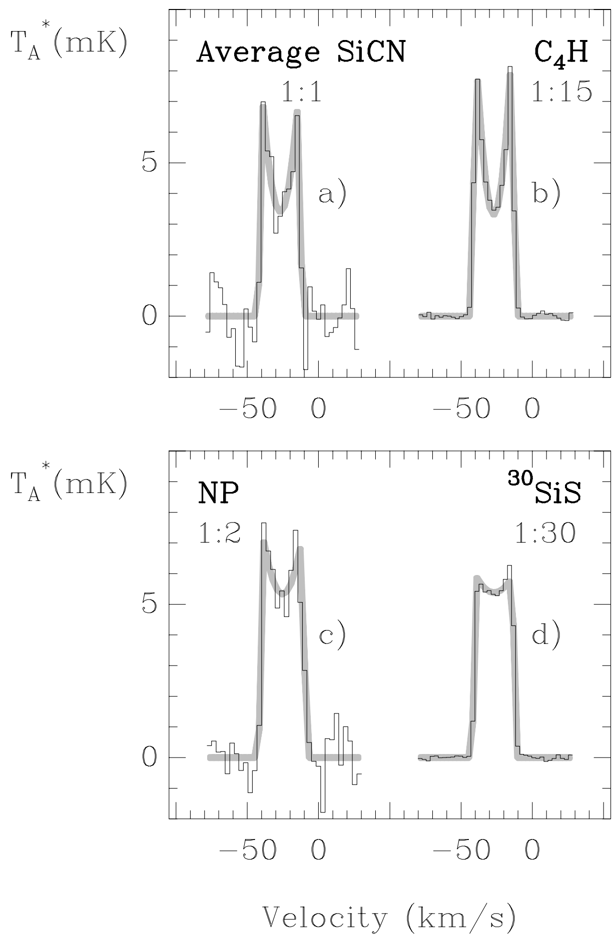

Fig. 2a–d. The SiCN line profile **a**, obtained by averaging the 4 unblended SiCN components of Fig. 1, compared to the profiles of the C_4H $\nu_7 = 2, l = 0, N = 11 - 10$ line **b**, the NP $J = 2 - 1$ line **c**, and the ^{30}SiS $J = 6 - 5$ line **d**. Note that the C_4H, NP and ^{30}SiS lines, which are much stronger than the SiCN line, have been multipled by 1/15, 1/2, and 1/30, respectively, in order to appear at the same scale.

The molecules confined in the thin outer shell of IRC +10216 have mm-line intensities which agree with those expected for a Blotzmann distribution of the rotational level populations (see Kawaguchi et al. 1995 and CGK). This probably means that they are collisionally excited, and that the physical conditions in the thin shell are fairly uniform. The rotation temperatures derived for the mole-
cules with moments of inertia and dipole moments similar to those of SiCN (HC_3N, C_3N, MgNC) are all in the range 20–30 K.

Assuming that the rotation temperature of SiCN is also in this range, we derive an SiCN column density along the line of sight (twice the radial column density accross the shell) of $\simeq 2 \times 10^{12}$ cm^{-2}. For this estimate, we have neglected the population of the $^2\Pi_{3/2}$ rotational ladder, which lies higher in energy by 71 cm^{-1} above the $^2\Pi_{1/2}$ ground state. The derived column density is ≃20 times smaller than the column density of SiC (Cernicharo et al. 1989) and MgNC, and about equal to that of MgCN (Ziurys et al. 1995). The abundance of SiCN relative to H_2, assuming it is confined to the thin 15″ radius shell where MgNC is observed, is 4×10^{-9} inside the shell.

We have also searched for the $J = 9.5 \rightarrow 8.5$ rotational transition of SiCCH, without success. None of its Λ-doublets could be detected, down to a limit of 38 mK.kms^{-1} (3σ), Taking into account the different dipole moments of the two species, the 3σ upper limit on the SiCCH abundance we derive is 0.8 of that of SiCN.

An Si-bearing molecule especially abundant in the outer envelope is SiC_2. The emission of its $4_{23} - 2_{22}$ transition, at 94.2 GHz, has been mapped with the IRAM interferometer (Lucas et al. 1994). Although SiC_2 is also observed in the inner circumstellar shell, its abundance peaks in the outer shell at a radius of 15″. This suggests that SiC_2 and SiCN could be formed simultaneously: the peak fractional abundance of SiC_2 is close to 10^{-6} and is two orders of magnitude larger than that of SiCN; hence, if SiC_2 is formed in situ, it may not be difficult to form enough SiCN by a parallel path.

In the ion-molecule scheme, SiC_2 comes from the reaction of Si^+ with C_2H or C_2H_2, leading to SiC_2H^+, followed by dissociative recombination of the latter ion (Glassgold et al. 1986). SiCN could result from parallel reactions of Si^+ with HCN, followed by the recombination of $SiCNH^+$. The reaction rate of Si^+ with HCN, however, is a factor of 10^3 smaller than that with C_2H (Millar et al. 1991). In this scheme, the low abundance of SiCCH can be explained by the difficulty of forming $SiCCH_2^+$.

SiC_2 and SiCN could also both be formed by radical-radical reactions involving the photodissociation products C_2H and CN. Alternately, these species could be synthesized on the surface of grains and released in space when the grains reach the outer envelope and are exposed to interstellar UV radiation (Guélin et al. 1993).

References

Apponi A.J., McCarthy M.C., Gottlieb C.A., Thaddeus P. 1999, ApJ 516, L103
Apponi A.J., McCarthy M.C., Gottlieb C.A., Thaddeus P. 2000, ApJ 536, L55 **AMGT**
Cernicharo J., Gottlieb C.A., Guélin M., Thaddeus P., Vrtilek J.M. 1989, ApJ 341, L25
Cernicharo J., Guélin M., Kahane C. 2000, A&A Supl. 142, 181 **CGK**
Glassgold A.E., Lucas R., Omont A. 1986, A&A 157, 35
Glassgold A.E. 1996, Annu. Rev. Astron. Astrophys. 34, 241
Guélin M., Lucas R., Cernicharo J. 1993, A&A 280, L19
Guélin M., Cernicharo J, Travers M.J. et al. 1997, A&A 317, L1
Langer W.D. et al. 1997, ApJ 480, L63
Lucas R., Guélin. M., Kahane C., Audinos P., Cernicharo J. 1994, Astrophys. Sp. Sci. 224, 293
Millar T.J., Rawlings J.M.C., Benett A., Brown P.D., Charnley S.B. 1991, A&A Suppl. 87, 585
Yamamoto S., Saito S., Guélin M. et al. 1987, ApJ 323, L149
Ziurys L.M., Apponi A.J., Guélin M., Cernicharo J. 1995, ApJ 445, L47