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INTERFEROMETER OBSERVATIONS OF CIRCUMSTELLAR ENVELOPES WITH THE IRAM PLATEAU DE BURE INTERFEROMETER

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ABSTRACT We summarize the main results obtained with the IRAM Interferometer on Plateau de Bure during its first years of operation, in the field of circumstellar envelopes.

INTRODUCTION

The rather simple geometry and kinematics of circumstellar envelopes make them ideal objects to study the astrochemical processes leading to molecule formation. Thermodynamic equilibrium chemistry, grain condensation and evaporation, ion-molecule reactions, and photodissociation all contribute to form around some stars an exceptionally rich chemical composition.

In recent years, rapid progresses have been made in the study of molecules in circumstellar envelopes. Molecules in the expanding shell of the IRC+10216 were first detected by radio observations in the early seventies, with the Kitt Peak radiotelescope. However, until the construction of large millimeter instruments in the eighties, and the development of very sensitive SIS receivers, only very few objects could be detected, and detailed observations were limited to a single object, the carbon-rich envelope of IRC+10216. In the last ten years, with the availability of the large single dishes, such as the 30m telescope of IRAM and the 45m telescope at Nobeyama, this field has rapidly developed. However circumstellar envelopes, due to their small angular size, are choice targets for still higher resolution instruments. The availability of large, sensitive millimeter-wave interferometers enables to image nearby objects such as IRC+10216, and to obtain crucial information to the morphology, dynamics, and radial distribution of various molecules in a number of circumstellar envelopes.

Comprehensive reviews of the observations of circumstellar envelopes are available (Omont 1992, Olofsson 1992, see also Lucas 1992). For a recent and general review of circumstellar chemistry the reader may refer to Omont (1990). We review here the first results obtained with the IRAM Plateau de Bure Interferometer. A description of the instrument may be found in Guilloteau et al. (1992).

MAPS OF IRC+10216

More than 50 different molecules, including highly refractory compounds, reactive species... have been observed so far in the dusty envelope of IRC+10216. The millimeter-wave emission from several of these species has been mapped with single-dish (e.g. 30 m telescope: Kahane et al. 1991) and interferometers (e.g. (Bieging and Rieu 1989), however, only in the cases of strong lines, and with a relatively low angular resolution ($\geq 10''$). With more sensitive instruments it is now possible to obtain very detailed information on this prototype object.

In order to investigate in more detail the formation and dynamics of molecules in this envelope, we have used the Plateau de Bure interferometer to map, with $3''$ and $5''$ angular resolutions, the emission from several species with different chemical characteristics: NaCl, a highly refractory molecule, thought to be exclusively formed in the stellar atmosphere; CCH, a product of photo/ion-molecule chemistry; SiC_2, which could be formed both in the stellar atmosphere and in the outer envelope; SiS, known to be present only in the inner part of the envelope; and HC_5N representative of the long carbon chains. With these observations, we were able to map also the emission from C_5H and from C_4H in its lowest bending mode (ν_7).

In a first set of measurements, we observed C_2H (N,J)=(1,3/2)–(0,1/2) (87.3 GHz) and vibrationally excited C_4H $\nu_7^2\Pi_{3/2}$ J=19/2–17/2 (87.3 GHz) in the upper sideband, and C_4H $\nu_7^2\Pi_{1/2}$ J=17/2–15/2 (84.1 GHz) and C_5H $^2\Pi_{3/2}$ J=35/2–33/2 (84.1 GHz) in the lower sideband. In a second step, we observed the NaCl J=7–6 (91.2 GHz) and SiC_2 $4_{2,3}$–$3_{2,1}$ (94.2 GHz). For each set of measurements, the source was observed in five interferometer configurations, with antenna spacings from 24 m to 200 m. For C_2H, we combined the interferometer data with a fully-sampled map, done with the 30 m telescope. For the other lines, a single spectrum from the 30 m telescope has been included in the *uv* data as zero spacing information. In a third set of observations, with six configurations (24 m to 300m spacings) providing a higher angular resolution, we simultaneously mapped the lines of SiS ($J = 5-4$) and HC_5N ($J = 34-33$).

The continuum emission (a point source) was subtracted of all line maps.

Our high resolution maps show marked deviations from spherical symmetry. (figure I).

The NaCl emission, resolved in both directions, is found to extend mostly along a SE–NW axis with PA $\simeq -20°$. There is no clear separation into red or blue-shifted velocities between the northern and southern "lobes". This North–South direction, nevertheless, could be that of strongest mass loss in the plane of the sky (Cernicharo et al. 1992).

The emission of SiCC (Lucas et al. 1992d) appears in the individual velocity-channel maps as coarse rings with highly clumped structure. Centered circular rings are the normal signature of a hollow shell with a constant expansion velocity. The rings, however, are not exactly centered on the continuum source, but slightly shifted to the east. The clumpy structure results either from abundance or excitation variations. Finally, the contours of the extreme channel maps (e.g. -12.6 km/s , -38.4 km/s) are elongated in the North-South direction.

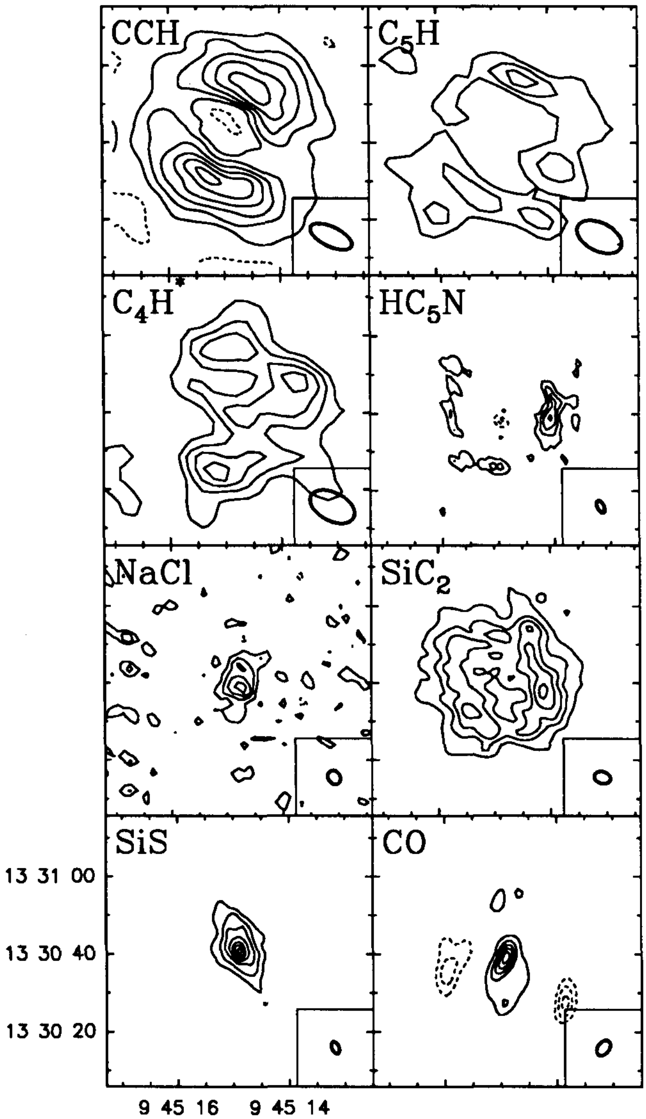

FIGURE I Maps of the circumstellar envelope of IRC+10216. Each box presents the average of the emission in a 5 km/s velocity interval centered on the star velocity (corresponding to a cut through the envelope by a plane perpendicular to the line of sight). The beam size is given in the lower right corner of each map. The CO observations (snapshots) miss most of the flux for this very extended envelope, but reveal the slightly elongated shape of the inner dense regions.

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As the previous interferometer maps (Bieging and Rieu 1989) our observations show that SiS is present in a compact source around the star, and thus traces the inner part of the envelope. We find that the source is clearly elongated along an axis close to the N–S direction (Lucas et al. 1992d).

The CCH velocity channel maps (Guélin et al. 1992) also show a clumpy ring structure. It is remarkable, however, that, although on the same slightly decentered rings, the CCH emission peaks are almost anti-correlated with those of SiCC (see e.g. the maps at −35 km/s). This may reflect a change in excitation conditions (C_2H is easier to excite than SiC_2, because of its lower dipole moment, and, as far as radiative excitation is concerned, because of the presence of a low lying $^2\Pi$ electronic state) or a change in chemistry (photodissociation of acetylene).

The C_5H and $C_4H(\nu_7)$ emission maps (Guélin et al. 1992) denote also a hollow shell distribution with a radius $r \simeq 20''$. This is rather surprising in the case of C_4H, since we are observing levels with energies of presumably $\simeq$ 200 K (see Yamamoto et al. 1987). The gas temperature in the envelope at $r = 20''$ ($\simeq 10^{17}$cm) is considered to be as low as 20 K (see e.g. Truong Bach et al. 1991). This suggests infrared excitation of the C_4H ν_7 state.

The high resolution HC_5N maps (Guélin et al. 1992) show that this molecule is present in a thin and clumpy extended shell. The general shape of the HC_5N shell resembles that of SiC_2; the western part is closer to the star and shows stronger emission.

HCN $V = 2$ MASER EMISSION IN IRC+10216

HCN $v = (0, 2^0, 0), J = 1 - 0$ emission was first detected by Lucas et al. (1986) with the 30-m telescope, at 89.088 GHz. It is a weak (0.3 K) line with a peculiar, asymmetric profile. Other C-rich sources (such as CIT 6) present strong maser emission in this line (Guilloteau et al. 1987, Lucas et al. 1988). Strong HCN maser emission in the $v = (0, 1^{1c}, 0), J = 2 - 1$ line is also found in IRC+10216 (Lucas and Cernicharo 1989), and numerous other C-rich envelopes.

Lucas and Guilloteau (1992a) have observed the $v = 2$ line in IRC+10216 with the IRAM interferometer. The continuum flux ($\sim$ 100 mJy) agrees with models of the photospheric and dust emission. The line emission is not significantly resolved, and the brightness temperature is $<$ 2000 K. This is consistent with weak maser emission, occurring within 5 stellar radii from the star ($0.5''$ diameter).

THERMAL SiO IN EVOLVED STARS

Lucas et al. (1992b), have observed the SiO v=0 J=2–1 emission from 12 evolved stars, mostly O-rich. Each star was observed for two or three snapshots, each one hour long, in three to six configurations with antenna spacings ranging from 24m to 300m. Simple source models were fitted in the visibility curves, thus determining fluxes and sizes. In some stars, the u, v coverage was good enough to obtain maps.

In RX Boo, R Cas, χ Cyg, and IK Tau, the emission is circularly symmetric and centered on the star's optical position. For the other objects the results are also compatible with that geometry. The half intensity sizes are 0.9″ to 2.4″. They are larger than those expected from previous work, though much smaller than the extents of CO (Bujarrabal and Alcolea 1991). SiO is widespread within the envelopes up to $\sim$ 1-7 10^{15} cm, and even further for the supergiants IRC+10420 and NML Cyg. The profile shapes are mostly gaussian, which indicates that the emitting regions do not have the expected high and constant expansion velocity. This is confirmed by the distribution of size as a function of velocity, which shows no clear increase at the line center. Grain formation is proposed to continue in O-rich and S-type Miras as far as 5 10^{15} cm from the central star, which would explain the large SiO abundance and extended acceleration region that are probably at the origin of the non-standard line profiles.

HCN IN O-RICH ENVELOPES

Guilloteau et al. (1992) have observed the HCN v=0 J=1–0 emission from O-rich evolved stars (detected at the 30-m by Nercessian et al. (1989). Each star was observed for two or three snapshots, each one hour long, in three to six interferometer configurations with antenna spacings from 24 m to 300 m. Simple source models were fitted in the visibility curves of all stars to determine fluxes and sizes. The u, v coverage was good enough to obtain reliable maps in several stars.

HCN is extended, at a distance of a few 10^{16} cm from the star, comparable to that of the 1612 MHz OH masers. These sizes are in agreement with the assumption that, in the envelopes of O-rich stars, HCN is formed by gas-phase reactions initiated by the photodissociation of CH_4, as proposed by Nejad and Millar (1988) and Nercessian et al. (1989).

SO_2 IN OXYGEN-RICH ENVELOPES

Sulfur is an abundant element, present in circumstellar envelopes in a variety of molecular compounds. H_2S was first detected in OH231.8+4.2 by Ukita and Morris (1983), while SO_2 and SO were found with the 30m (Lucas et al. 1986, Guilloteau et al. 1986). A systematic study of SO_2, SO, H_2S has been undertaken with the 30m (Omont et al. 1991). H_2S was detected in 15 O-rich stars in its ortho and para states. The line profiles of H_2S are much narrower than those of SO_2, which indicates that H_2S is present in the inner regions (where acceleration probably occurs), while SO_2 (and probably SO) are in an outer shell. Modelization of the H_2S emission shows that it comes from a region of radius $\simeq 10^{16}$ cm. SO_2 and SO are formed by reactions of S with OH, in the H_2O photodissociation region (a few 10^{16} cm).

We have checked this by observing SO_2 in three O-rich stars (OH26.5+0.6, IRC+10011, IRC+10420). The results are consistent with the above formation mechanism for SO_2.

THE 200 km s^{-1} BIPOLAR OUTFLOW IN CRL618

This outflow, discovered by Cernicharo et al. (1989) has been observed in HCN $J = 1 - 0$ with the Plateau de Bure interferometer (Neri et al. 1992). The angular resolution was 2.4″.

The circumstellar envelope itself is extended (diameter 3.2″ at half power, but detectable in 10″), and centered on the radio continuum source. The profile is parabolic for the positive velocities (far side), while the continuum radiation is absorbed at negative velocities.

The red-shifted outflow emission comes from a an unresolved region 1″ to the west of the HII region, while the blue-shifted high-velocity gas arises from a source of size $\simeq$ 2″, partly in front of the HII region. The high velocity HCN is proposed to be formed behind shocks at the wind-envelope interface surface.

THE PRE–PLANETARY NEBULA CRL 2688

CRL 2688 is the prototype object for pre–planetary nebulae with bipolar structure. Numerous molecular species are detected with single dishes. The line profiles differ from species to species: some of them, like CO, HCN or SiS, present high velocity wings.

Maps of SiS and HC_5N have been obtained with IRAM interferometer (Lucas et al. 1992c). These maps are shown in Figure II. The continuum flux is 170 mJy, and is extended (about 2″ intrinsic size). The source of the SiS emission is compact and traces both the low velocity and high velocity outflows: the high velocity outflow is oriented along the axis of the optical bipolar nebula, while the low velocity outflow may come from a rotating, expanding disk/torus. The HC_5N is extended in a hollow, expanding, maybe rotating, shell. Detailed modelling of this source is being made.

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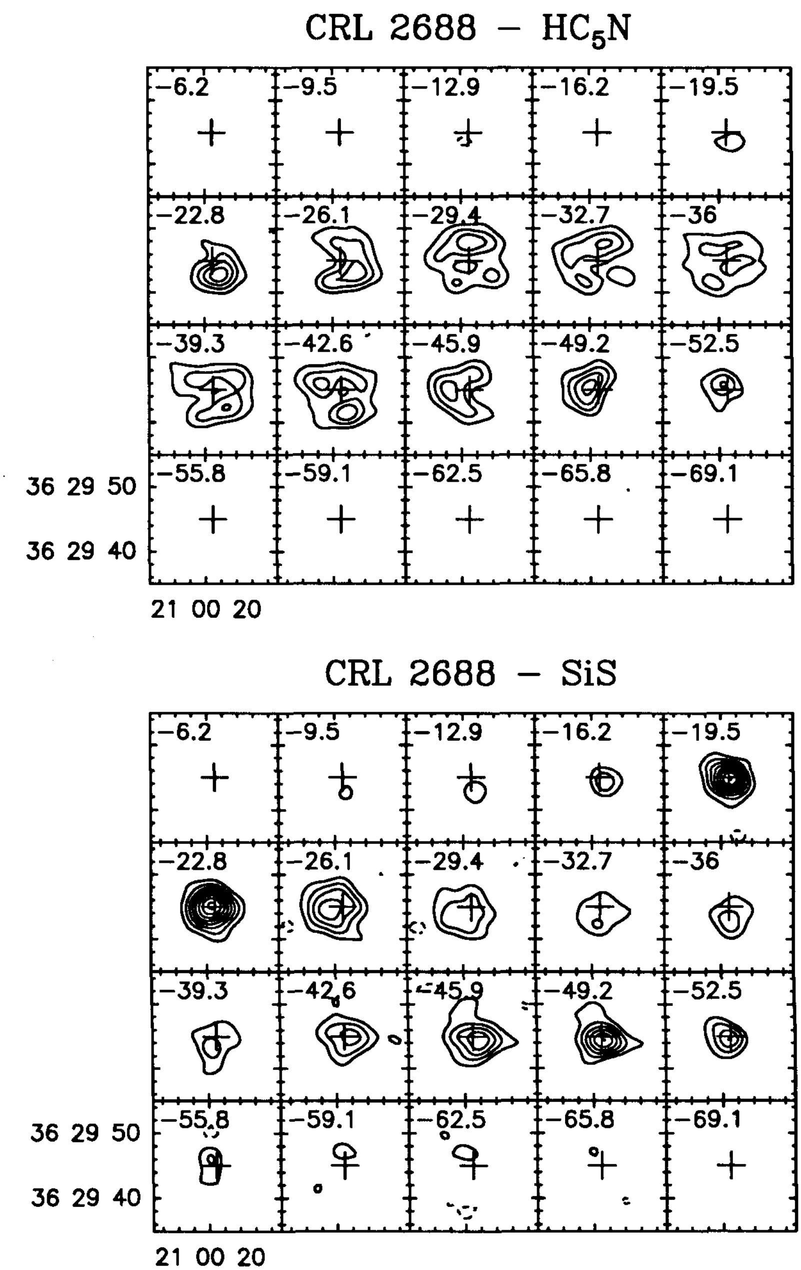

FIGURE II HC_5N and SIS maps of CRL 2688 obtained with the Plateau de Bure Interferometer. The angular resolution is $3.6 \times 2.9''$. The contour spacing is 40 mJy/beam for both maps.

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