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Abstract

Recent observations of circumstellar shells at arc second resolutions (e.g. 10^2 $R*$ in the case of IRC+10216) reveal clumpy structures, asymmetries and jets. The most recent maps of such objects, observed with the IRAM Plateau de Bure interferometer and Pico Veleta telescope, are presented.

1.1 Introduction

The dusty envelopes of late type stars are fascinating objects on their own; they are also interesting for what they teach us about IS chemistry. From their velocity field and density profile, we can study the mass loss during a crucial phase of stellar evolution: since the gas expands at nearly constant velocity in all, but the innermost envelope, the velocity maps yield a 3-D view of the molecule spatial distribution; the distributions of the different molecular species show how photochemical, molecule-molecule and grain-surface reactions proceed with time in a well behaved environment.

The closest massive envelopes lie a few hundred parsecs away and have small angular sizes. The construction of large millimeter-wave interferometers, in particular the IRAM Plateau de Bure interferometer (Guilloteau *et al.* 1992), has provided a major breakthrough in their investigation.

1.2 Molecular emission in IRC+10216

The most remarkable and probably closest massive envelope surrounds the bright IR object IRC+10216 (CW Leo). Its outer radius, observed in the mm lines of ^{12}CO, the most abundant molecule and the best shielded from photodissociation after H_2, is $R = 3'$ (Guélin & Cernicharo, *in preparation*).

Its warm 'core', where about 50 different molecules are detected, has a radius of $\simeq 15''$.

The IRAM Plateau de Bure interferometer is ideally suited to study the IRC+10216 core. Its primary field has a FWHP of 55″ at 90 GHz and its synthetized beam can be as small as 2″. The large effective area of the instrument (460 m^2 since April 1993) makes it sensitive enough to map with a few arcsec resolution scores of molecular lines. The possibility to observe simultaneously two 500 MHz-wide IF bands with a good frequency resolution, allows to study 5–10 lines in a single observing session.

A programme of mapping the λ 3 mm lines of the chemically most significant molecules is under way at Bure (Lucas et al. 1992, Guélin et al. 1993, Lucas 1994, Lucas et al. *in preparation*). 14 molecules have been observed to date: CO, CS, C_3S, SiO, SiS, SiC_2, HC_5N, the carbon-chain radicals C_nH, n = 2–6, and the metal compounds NaCl and MgNC. The synthetized beam HPW range from 3″ to 10″ (for CCH and C_5H, two of the very first maps observed with the Bure interferometer). In addition, vibrationally excited lines of C_4H (Lucas 1994) and HCN (Lucas & Guilloteau 1992) have been observed.

In a complementary programme, higher energy 2 mm and 1.3 mm lines of HC_3N, C_4H, SiC_2, SiS, etc... have been mapped with the IRAM 30-m telescope. The HC_3N 1.3 mm data illustrate the importance of the excitation conditions in the derivation of molecular column densities (Audinos et al. 1994).

Figure 1.1 shows the brightness distributions observed for the N= 10–9 C_4H line in adjacent 3 kms^{-1} wide channels. A point-like continuum source, coincident in position with the compact IR source and the central star, was removed from the maps. The source position is denoted by a cross at the center of the field.

The IRC+10216 envelope is known to expand with a fairly constant radial velocity (-14.5 kms^{-1}), so that each velocity-channel sees the emission from a conical sector axed on the line of sight. The lowest and highest velocities arise from two narrow cones, respectively on the near and rear sides of the envelope. The velocities close to $v_{sys} = -26.5$ kms^{-1} arise from the vicinity of the meridian plane.

The maps of Figure 1.1 have the appearance expected for a hollow spherical shell: the extreme velocity-channel maps show unresolved disk-like sources, whereas the median velocity-channels, which represent the line brightness distribution across the meridian plane, show broad ring-shaped sources. It is worth noting that the C_4H sources, although almost perfectly circular, are not centred on the star (cross), but 2–3″ more to the east.

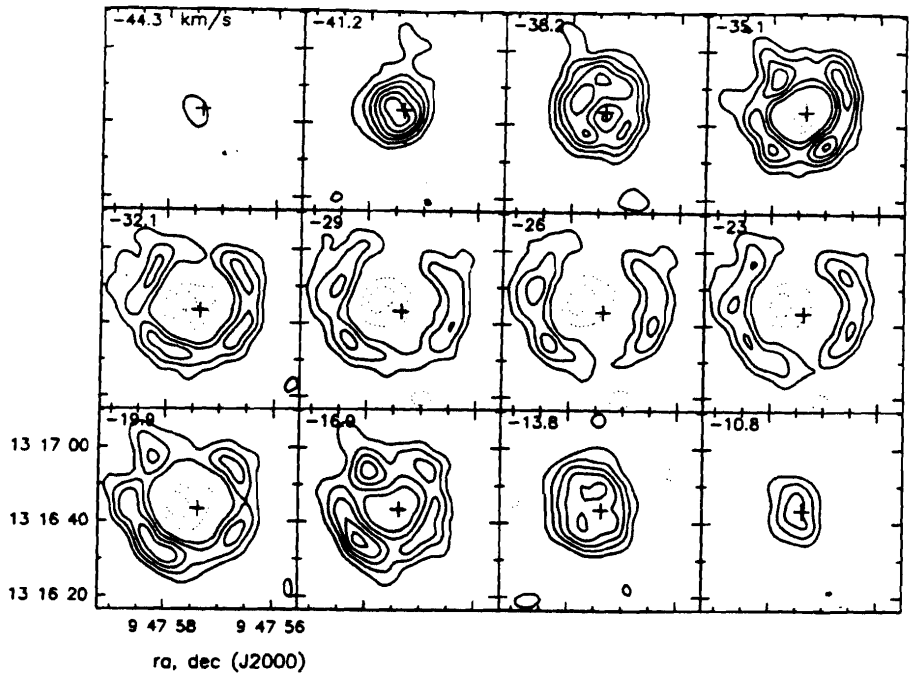

Fig. 1.1. Velocity-channel maps of the C_4H N= 10–9 line emission in IRC+10216, observed with the Plateau de Bure interferometer. The synthetized beam has a FWHP of $5 \times 5''$. A point-like continuum source of 66 mJy, coinciding with the central IR source (cross) has been removed from the maps (Guélin et al. 1993).

The 3 mm lines of several other molecules and radicals (HC_5N, C_3H, MgNC,...) show very similar brightness distributions (see e.g. Fig. 1.2). They arise mostly from a few arcsec thick shell with a radius of $\simeq 15''$. The velocity-channel maps have all the same clumpy appearance (the bright clumps lying often at the same positions) and show all intensity minima to the N and to the SE.

The ring, or hollow shell appearance of the brightness contours of Fig. 1.1 is not common to all molecules. One third of the species mapped so far show centrally peaked distributions. Figure 1.3 shows the brightness distribution of the J=5–4 line of SiS. The SiS source is much more compact than the C_4H and C_3H sources and fits inside the 'hole' in the center of these latter. It is also elongated in the NS or NE-SW direction, i.e. more or less in the direction joining the minima of the C_4H 'ring'.

The differences between Fig. 2 and Fig. 3 cannot be explained by the envelope structure and/or line excitation effects. Obviously, the 'central

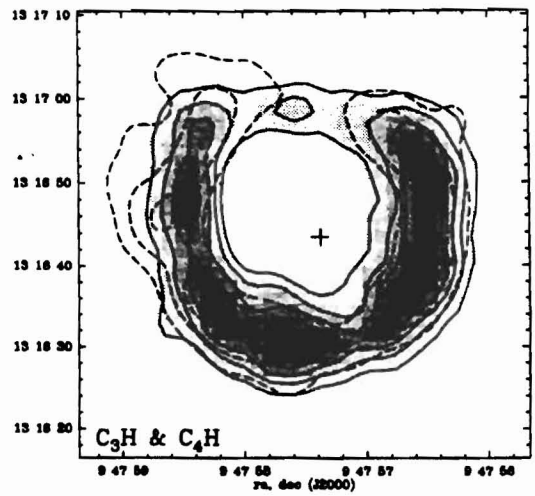

Fig. 1.2. The intensity distributions of the C_3H, $^2\Pi_{1/2}$J= 9/2–7/2 line (solid contours) and the C_4H, N= 10–9 line (dotted contours), observed in IRC+10216 with the Plateau de Bure interferometer (Guélin et al. 1993). The intensities are integrated over the velocity interval -34 kms^{-1} $< v <$ -21 kms^{-1} and the peak intensity of each species normalized to 1; the contours are equally spaced. The angular resolution is 5″ × 5″. The maps are not corrected for attenuation by the primary beam (HPBW 50″).

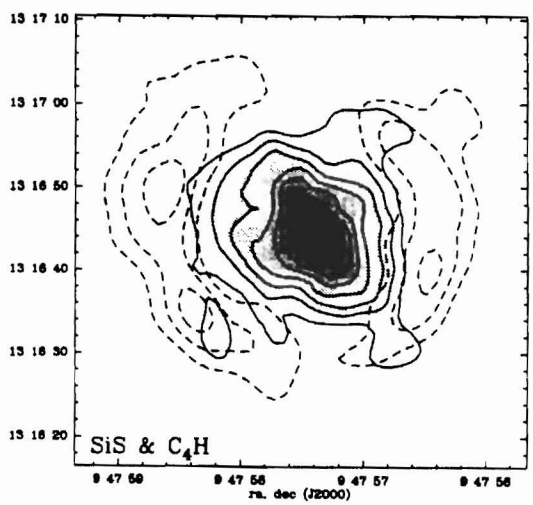

Fig. 1.3. The intensity distributions of the SiS, J= 5–4 line (solid contours) and of the C_4H N=10–9 line (dotted contours), observed in IRC+10216 with the Plateau de Bure interferometer (Lucas, 1994). The intensities (normalized to 1) are integrated over a 3 kms^{-1}-wide band centred on v_{sys} = -26.5 kms^{-1}. The angular resolution is 3″ × 3″ for the SiS line, 5″ × 5″ for the C_4H line.

hole' in Fig. 1.3 is not due to lack of gas and the central peak of Fig. 4 is not just an excitation artifact: it is observed as well in the easy to excite CO molecule (dipole moment μ = 0.11 D), as in the hard to excite species SiS and NaCl (μ = 10 D); it is not observed in C_4H (μ= 0.7 D), HC_5N (μ = 4 D) and MgNC (μ = 5 D). These differences must result from chemistry.

1.3 Chemistry in IRC+10216

The gas phase chemistry in IRC+10216 has been modelled by several authors (McCabe et al. 1979, Lafont et al. 1982, Glassgold et al. 1986, Nejad & Millar 1987, Cherchneff et al. 1993). Interstellar UV penetrates into the outer envelope ($R >> 20R_*$) and dissociates the 'parent' molecules (CO, HCN, H_2C_2,...) expelled by the central star. The radicals and ions produced by photodissociation fuel a rich gas phase chemistry which can form fairly complex molecules, such as the long cyanopolyynes HC_nCN, n= 2–6. In the model of Cherchneff et al. (1993a,b), SiS is a 'parent' molecule coming from the stellar atmosphere. Its distribution should peak on the star, as is observed in Fig. 1.3 . C_4H is formed from CCH by radical-radical reactions in the outer envelope. It should thus have a shell-like distribution, as is observed in Fig. 2. For a mass loss rate of 2 $10^{-5} M_{\odot} yr^{-1}$ and a 'normal' interstellar UV field, Cherchneff et al. predict a radius of the C_4H shell of 4–5 10^{16} cm, in perfect agreement with what is observed.

The observed maps are however much too detailed to be fully explained by simple chemical models. According to Cherchneff et al., C_3H is formed by radiative association, a much slower process than the C_2H+C_2H reaction leading to C_4H; its abundance should peak at a larger distance from the central star. The great similarity of the C_3H and C_4H maps, in particular as concerns the extent of the emission, implies either that the shell observed in Fig. 1.2 marks the edge of the dense envelope, or that the three molecules are formed and destroyed together at a much faster rate than calculated by Cherchneff et al. (1993).

Desorption of molecules from grain mantles could offer an interesting alternative to the relatively slow gas phase reactions. Desorption could result from irradiation by interstellar UV photons or, if the molecules are weakly adsorbed, from shocks. In all cases, the bright spots on Fig. 1.2, which are observed for molecules with very different excitation conditions, must correspond to high density clumps.

The bright rings on Fig. 1.2 appear dimmer to the N and the SW. A similar pattern is observed for about all the molecules showing a shell-like brightness distribution. Very probably, these dark areas correspond to holes

in the envelope. The holes define a N-SW axis roughly aligned with the major axis of the SiS source (Fig. 1.3) and with that of the IR source (Dyck et al. 1987). The outflow from the central star may not be as symmetrical as suggested by the fairly spherical CO outer envelope and may occur preferentially along a N-S axis, roughly perpendicular to the line of sight.

1.4 The very fast outflow in CRL 618

Whereas bipolar outflow and shock chemistry are only suggested in IRC +10216, they are flagrant in the more evolved stellar envelope CRL 618. CRL 618, which is thought to be a 'proto planetary nebula' at the end of the high mass loss phase, has already developped a compact HII region at the center of its thick dusty envelope. The central star, hidden by dust, has reached the temperature of a B0 star; it is surrounded by two optical nebulosities showing high expansion velocities in the Hα and [NII] lines (Carsenty & Solf 1982). The distance to CRL 618, although very uncertain, is estimated to be *circa 1.7* kpc.

Molecular line observations show, like in IRC+10216, an extended molecular envelope ($R \simeq 40''$) with a compact dense core ($R = 3''$) expanding at fairly constant velocity (20 kms^{-1}). Inside the core, one observes a bipolar outflow with a very large velocity (150–200 kms^{-1}) in the lines of half a dozen of molecules (Cernicharo et al. 1989).

The envelope core and the fast molecular outflow have been mapped in several molecular lines, including the 2–1 (Cernicharo et al. 1989) and 3–2 (Neri et al. *in preparation*) lines of CO, using the IRAM 30-m telescope (resolution 12″ and 9″). The HCN 1–0 line has been mapped with a 3″ resolution with the IRAM Plateau de Bure interferometer (Neri et al. 1992). The high velocity HCN emission arises from a barely resolved source ($2'' \times < 0.5''$) elongated in the EW direction and aligned with the optical lobes. Like in Hα, the HCN blue lobe is to the E and the red lobe to the W, the outflow axis being probably inclined by 45° with respect to the line of sight (Figure 1.4).

Observing molecules with such large velocities with respect to the surrounding gas (200 kms^{-1} versus 20 kms^{-1}) is surprising. It is known that almost all molecules are dissociated in a shock with $\Delta v > 50$ kms^{-1} (Hollenbach & McKee 1980). The high-velocity gas is likely to have been shocked and its molecules dissociated; the observed molecules must have reformed after the shock. The outflow of CRL618, whose geometry and time scales are roughly known, offers thus a text-book case of post-shock chemistry.

According to the interferometric data of Neri et al. (1992), the high-

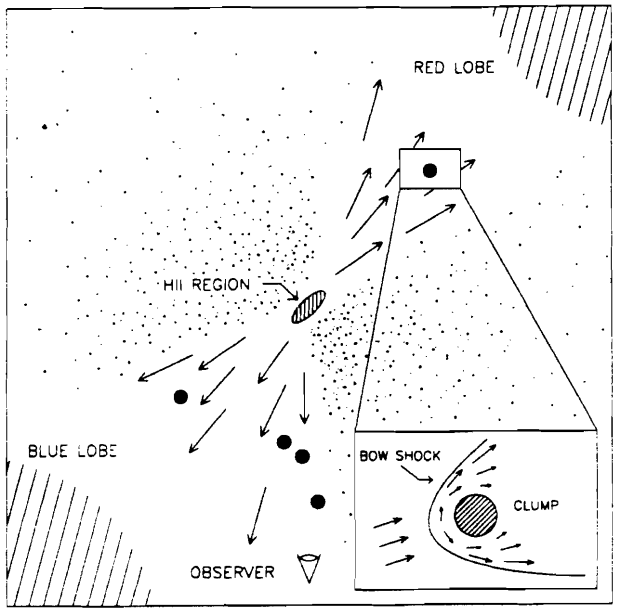

Fig. 1.4. Morphology of the envelope core and high velocity outflow in the proto planetary nebula CRL 618, as derived from HCN J=1–0 interferometric data and from Hα measurements. The HII region lies at the center of a compact and rather spherical core, itself surrounded by a low density halo (extending beyond the edges of the figure). A highly energetic flow collimates stellar material along an axis inclined by about 45° on the line of sight. Impacts of the flow on dense envelope clumps induce strong shocks. The high velocity wings of the HCN line arise from turbulent flows behind these shocks (Neri et al. 1992).

velocity HCN emission arises from several unresolved sources located at 3 10^{16} cm from the star. The sources probably result from the impact of a primary outflow on dense envelope clumps (see insert in Fig. 1.4). The HCN reformation time is found to be < 50 yr. The relative HCN and CO abundances in the high-velocity gas are consistent with those calculated by Neufeld & Dalgarno (1989) for post-shock chemistry in carbon-rich gas.

It will be interesting to reobserve the HCN line in several years to check whether the outflow geometry and molecular abundances have changed.

1.5 Other envelopes

Other high resolution maps of molecular emission have been made with the Bure interferometer on CRL 2688, another 'proto planetary' C-rich nebula

(HC_5N, SiS, see Lucas 1994) and on NGC 7027, a planetary nebula (HCO^+, see Cox et al. 1994). These maps, like those of IRC+10216 and CRL 618, show clumpy structures and deviations from spherical symmetry.

An ambitious programme aimed at measuring the sizes and asymmetries of a large number of thick circumstellar envelopes is carried out at Bure and Pico Veleta. Fifty stars of various types, known to be surrounded by conspicuous envelopes, have been observed in the mm lines of ^{12}CO (Neri et al. *in preparation*); a subset of this sample has also been measured in SiO (Lucas et al. 1992). The Bure observations have been made in the 'snapshot' mode. For most objects, the sampling of the UV plane is too loose to yield images of the molecular emission as detailed as those of Figs. 1.2 &1.3; they allow however to derive for each envelope the line radial brightness distributions in the different velocity-channels, as well as to measure the degree of ellipticity and the position angles of the envelopes.

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