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Carbon-chain molecules as tracers of time-dependent chemistry

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Gas-phase chemical models seem able to reproduce the abundances of organic interstellar molecules, provided the clouds are relatively young. Age, however, is not observationally constrained in most astronomical sources. An exception is IRC+10216, an expanding circumstellar envelope, where the distance to the central star is also a measure of age. An analysis of the spatial distribution of carbon chains in that source shows that the agreement between predicted and observed abundances is fortuitous.

That long carbon-chain molecules could be abundant and play a large role in interstellar chemistry was first recognized twenty years ago with the discoveries of HC_5N, C_3N and C_4H in Sgr B2, in the circumstellar envelope IRC+10216, and in the dark cloud TMC1. To date, 7 acetylenic chain radicals, C_nH, $n = 2 - 8$ (Guélin et al. 1997) and 5 cyanopolyyne molecules, $HC_{2n}CN$, $n = 1 - 5$ (Bell et al. 1997), are detected in TMC1 and/or IRC+10216. In contrast, only two cyanopolyyne radicals, C_3N and C_5N are known.

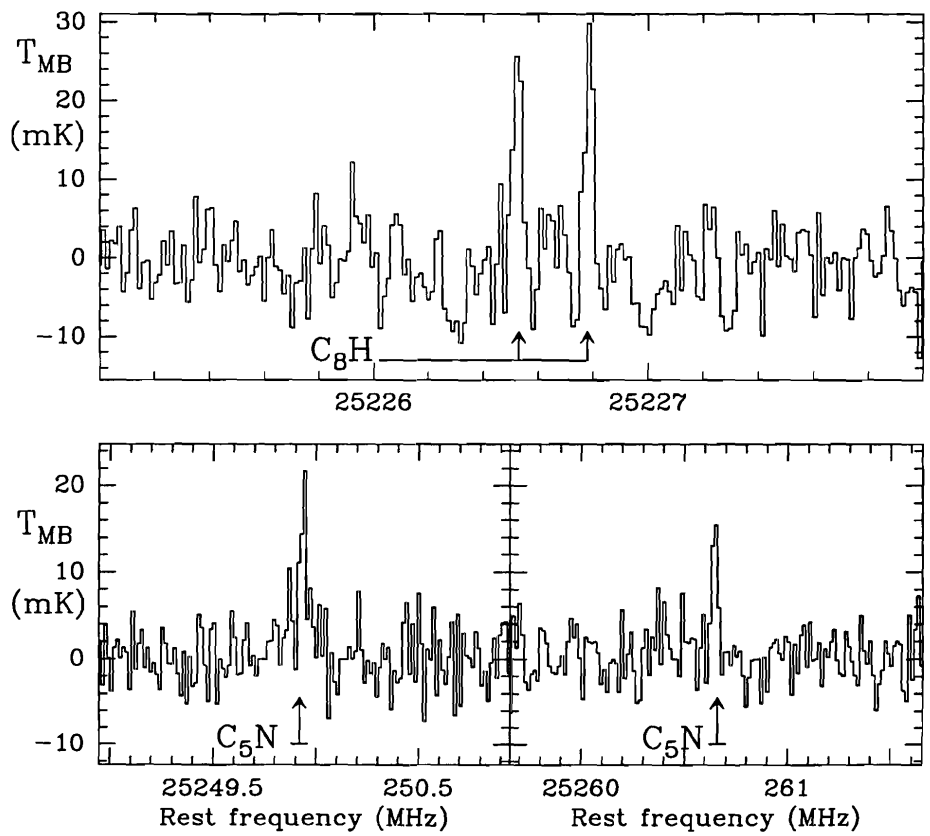

Fig. 1: The C_8H $^2\Pi_{3/2}$, $J = 21.5 \rightarrow 20.5$ (upper spectrum), C_5N $^2\Sigma\, N, J = 9, 9.5 \rightarrow 8, 8.5$ (lower left) and C_5N $N, J = 9, 8.5 \rightarrow 8, 7.5$ (lower right) rotational line components, observed in the direction of the TMC1 cyanopolyyne peak with the Effelsberg telescope (see Guélin et al. 1998).

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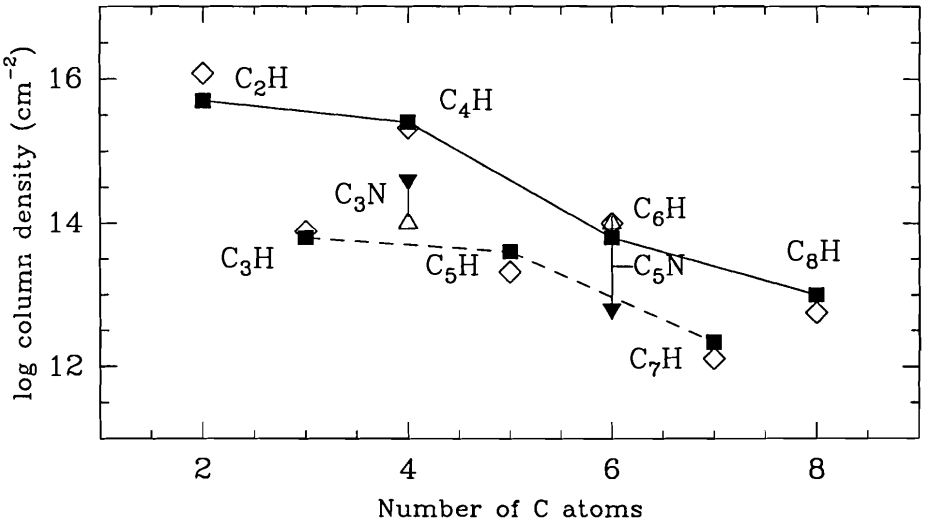

Fig. 2: Observed (filled symbols) and predicted (open symbols) column densities of the carbon-chain radicals in IRC+10216 (after Guélin et al. 1997&98). The predicted column densities are taken from Millar & Herbst (1994) and correspond to the peak abundances of the different species.

Figure 1 shows three spectra, observed with the Effelsberg telescope in the direction of the TMC1 cyanopolyyne peak. The spectra cover the C_8H $^2\Pi_{3/2}$, $J = 21.5 \rightarrow 20.5$ and C_5N $^2\Sigma$, $N = 9 \rightarrow 8$ rotational lines, which appear each as two 0.3 kms^{-1}-wide features, separated by 0.25 MHz and 10.7 MHz, respectively. The long carbon-chains are the heaviest molecules identified without doubt in space. They tend to be abundant in the same sources and, therefore, are probably formed by similar chemical processes. Their study offers thus a unique opportunity to test our understanding of interstellar chemistry.

Unfamiliar on earth, the carbon-chain molecules are thought to form in the gas phase by reactions of C, C^+, N, CCH and CN with polyacetylenes and polyacetylenic ions. They are destroyed by similar-type reactions leading to higher order members, as well as by photdissociation. Time-dependent chemistry models (Herbst et al. 1994, Howe et al. 1996) succeed in reproducing the observed carbon-chain abundances, but only after a fine tuning of the acetylene abundance and cloud age, two parameters poorly constrained by observations. (The abundance of C_5N, the latest discovered carbon-chain radical, is too large by a factor of ~ 10, mostly because the reactions leading to C_7N are not included in the models). The predicted carbon-chain abundances, however, depend critically on the cloud age, so that their agreement with the observed abundances may be *ad hoc*.

In the case of IRC+10216, age is not anymore a free parameter, as the envelope is resolved and its expansion velocity is constant and well known. Figure 2 compares the observed C-chain peak abundances in that source to those predicted by Millar & Herbst (1994) for a medium-high acetylene abundance ($2.5\ 10^{-5}$ with respect to H_2). The agreement is remarkably good, except for C_5N.

Figure 2, however, is misleading, as the models predict that the longest chains form from the shortest chains, thus appear later and at larger radii. This is not observed. Figure 3 shows the observed brightness distributions of C_2H, C_4H and C_6H in a plane passing through the central star: the 3 maps look very similar and their emission peaks lie all on a same circle, whose radius is $16''$ ($\sim 5\,10^{16}$ cm). The emission peaks of the lines of vibrationally excited C_4H lie also on the same circle, which shows that line excitation plays a minor role in the shape of Figure 3, so that this figure mostly reflects the molecule abundance distributions.

The models of Cherchneff & Glassgold (1993) and of Millar & Herbst (1994) predict that C_6H forms from C_4H and C_4H from C_2H. C_2H itself results from the photodissociation of acetylene. A lower limit to the formation times of C_4H and C_6H can be derived by using the largest possible reaction rates, gas density and acetylene abundance. It takes ≥ 1000 yr to form C_4H from C_2H and C_6H from C_4H, which means that the abundances of these species should peak respectively $\simeq 14''$ and $\simeq 28''$ further out than C_2H. In contrast, Figure 3 shows that the 3 species coexist spatially within $\leq 2''$ and should be formed quasi-simultaneously (i.e. within 140 yr – see below).

The very good agreement of Figure 2 is thus fortuitous and a new formation mechanism must be sought. This mechanism could be the desorption from dust grains of weakly attached carbon-chains, under the influence of interstellar UV and/or shocks (Guélin et al. 1993).

This is illustrated in Fig. 3, where the intensity distribution in the $\lambda 3$ mm lines of C_2H, C_4H and C_6H is integrated over a narrow velocity band centred on the star velocity (-26.4 kms^{-1}). The contours reflect the molecular abundance distributions in a plane perpendicular to the line of sight and passing through the central star. The envelope is known to be nearly spherical and to expand radially with a 14.5 kms^{-1} velocity. The distance to IRC+10216 being ~ 200 pc, $1''$ corresponds to $\sim 3\,10^{15}$ cm in the plane of Fig. 3, and it takes $\simeq 70$ yr to the expanding gas to cross such a distance in the radial direction. C_2H, C_3H, C_4H, C_5H, and C_6H are all observed in the same thin shell of radius $15''$ and width $\simeq 3''$. They must be formed quasi-simultaneously in less than 200 yr, whereas the fastest ionic and neutral gas phase reactions must have timescales

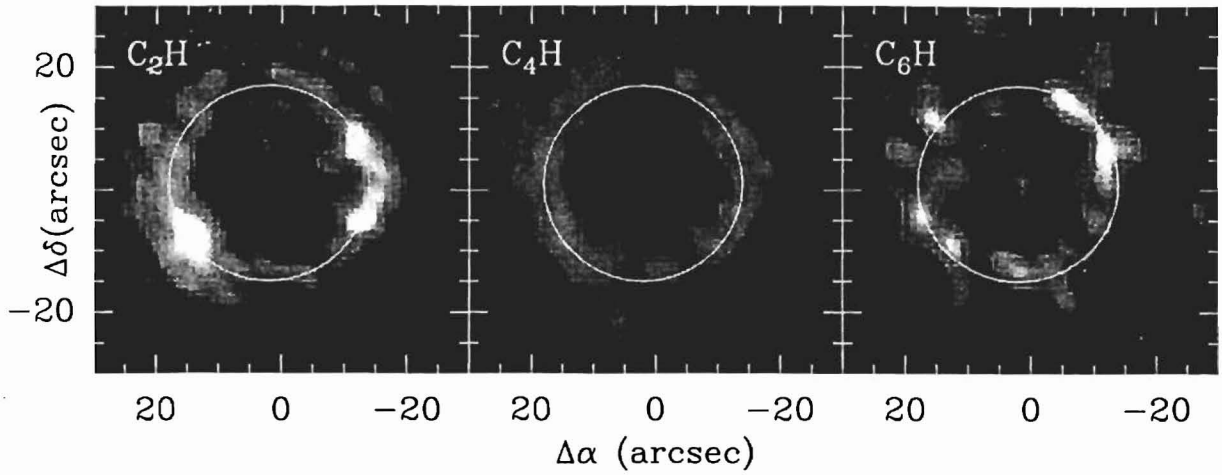

Fig. 3: Brightness temperature distribution of the λ 3-mm lines of C_2H, C_4H and C_6H, observed in IRC+10216 with the IRAM interferometer. The intensities (multiplied by 1,1.3, and 7, respectively) have been integrated over a narrow band centred on the star velocity and represent roughly the species' abundance distribution in a meridian plane. Except for the larger noise in C_6H, the 3 maps look very similar; their brightest spots lie all along a circle of radius 16″. Note that the emission from the central star has been removed.

$> 10^3$ yr at this distance from the star. This suggests that faster processes, such as the release of radicals formed on grain surfaces, might be at stake. Such a release could be triggered by the interstellar radiation field when the grains drift into the poorly shielded parts of the outer envelope, or simply by shocks.

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