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FROM DUST TO GAS ... AND THE INFRARED TO THE MILLIMETRIC: DOUBLY DEUTERATED MOLECULES IN PROTOSTARS

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In recent years, multiply deuterated molecular species have been detected towards many protostellar sources with abundances much higher than the cosmic abundance of deuterium would suggest. These results still pose somewhat of a challenge for the chemical models of the ISM, but might bring very important new clues about the chemical evolution of protostars, particularly about the chemical interplay between dust and gas in those objects. A proper understanding of this gas–grain interplay will only be obtained by combining spectroscopic millimetric observations of the gas with spectroscopic infrared observations of the dust-grain contents.

Chemistry is increasingly believed to play an important role during the very first stages of star formation because certain key molecular species, such as water (H_2O) or carbon monoxide (CO), can strongly affect the evolution of pre- or protostellar system by modifying their thermal balance or affecting the ambipolar diffusion processes. An important aspect of the chemical evolution of protostellar systems is the interplay between the gas and the dust grains. In the quiescent interstellar medium, many of the metals are stuck onto the dust grains, and therefore removed from the gas. Even stronger depletion is found in the prestellar cores—the alleged immediate precursors of protostars—because of the low temperatures and high densities there. Once a protostellar source has formed, however, associated energetic phenomena will reverse that trend. The heating due to the central object, or the shocks associated with the supersonic jets powered by it, will re-inject a significant fraction of the dust-grain content back into the gas phase. This will strongly affect the chemical composition of star forming regions, and lead to time-dependent chemistry.

In order to properly understand the chemical evolution of protostars, it is therefore of prime importance to understand the interplay between gas and dust. A useful indicator of such interplay is the chemistry of deuterium because the removal of CO from the gas phase through depletion (Roberts & Millar 2000a, b), and the chemistry occurring onto the dustgrains themselves (Tielens 1983) can greatly enhance the relative abundance of deuterated species over their hydrogenated counterparts. This can lead to an an extremely large overabundance of deuterated molecules, particularly of multiply deuterated species.

The first detection of a multiply deuterated molecule in space (doubly deuterated formaldehyde) was obtained by Turner (1990) in the direction of the Orion Hot Core. Turner showed that the abundance of the doubly deuterated form of formaldehyde (D_2CO) was about 0.3% that of the normal (H_2CO) form. Since the cosmic abundance of deuterium is about 10^{-5} (Lemoine et al. 1999), this already represents an over-abundance of about 7 orders of magnitude . . . Subsequently, D_2CO was also detected in the low mass protostellar system IRAS 16293–2422 (Ceccarelli et al. 1998) with an abundance of about 5–10% that of the hydrogenated form (Loinard et al. 2000). This is an overabundance of 9 orders of magnitude! Even larger overabundances of D_2CO ($[D_2CO]/[H_2CO] \sim 20\%$) were found in another (possibly younger) low mass protostellar system (16293E) where the doubly deuterated form of ammonia (ND_2H) was also detected, with an abundance ratio $[ND_2H]/[NH_3]$ of about 3% (Loinard et al. 2001).

In order to assess whether such large enhancements are a usual feature of low mass protostellar systems, we searched for D_2CO in a large sample of objects associated with star formation (Loinard et al. 2002). D_2CO was detected in the 20 low mass protostars of our sample, with $[D_2CO]/[H_2CO]$ abundance ratios between 2 and 40%. On the other hand, we failed to detect D_2CO in the more massive protostars in our sample, as well as towards shocks associated with the molecular outflows powered by low mass protostars (Loinard et al. 2002). The typical upper limits on the $[D_2CO]/[H_2CO]$ ratio for massive protostars and shocks is of the order of 0.5%.

Reactions onto the dust grain surfaces can strongly favor deuteration over hydrogenation, particularly for formaldehyde, in cold and dense environments (Tielens 1983). Hence, the detection of multiply deuterated molecules in low mass protostars strongly suggests that active grain surface chemistry is at work. In this scheme, the deuteration itself would have occurred during the cold prestellar phase (indeed when the depletion is highest), while the injection of deuterated material into the gas phase would occur during the protostellar phase thanks to heating by the central sources (Ceccarelli et al. 2001). Since high mass stars tend to form in warmer environments, it is quite natural that they would have lower levels of deuteration. Moreover, the highest levels of deuteration are only expected in those centers of the cores that have reached the highest levels of densities during the prestellar stage, which explains why shocks along molecular outflows exhibit lower levels of deuteration.

Recently, however, gas-phase schemes have been put forward to explain the high levels of deuteration in low mass protostars (Roberts & Millar 2000a, b; Rodgers & Charnley 2001). The detection of doubly deuterated ammonia in 16293E (Loinard et al. 2001) and L134N (Roueff et al. 2000) might be more easily explained through those schemes. It is important for our understanding of the chemical evolution of protostars, as well as for our general understanding of astrochemistry, to assess whether the deuteration occurs on the dust grains or in the gas phase. Although a study of the deuteration of more molecular species might bring important clues to the issue, direct observations of the dust content in protostellar sources could provide the most reliable answer.

While the molecular gas content of protostellar sources is most easily probed using millimetric and sub-millimetric observations, the content of the dust grains can be measured using near- and mid-infrared spectroscopy (between about 1 and 20 μm). Solids (such as water, carbon monoxide, methanol, etc.) are detected by the absorption bands they produce. Measuring the relative abundance of the various molecules in the dust-grains of protostellar sources could provide very stringent constraints on the chemical origin of the deuteration there. Much has been learned about the dust content of young stellar objects (YSOs) thanks to *ISO*. However, *ISO* observations have often focused on massive YSOs, which are much brighter in the infrared than their lower mass counterparts. As the observations of doubly deuterated formaldehyde presented above show, however, the chemistry of low mass objects is not a scaled down version of that in higher mass sources. It is therefore important to obtain deep spectroscopic near- and mid-infrared observations of low mass YSOs to better understand their chemical composition. A 10 meter telescope, such as the GTC, equipped with a sensitive mid-infrared spectrometer could play an important role in this respect.

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