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HH ILLUMINATION OF CLUMPS WITHIN MOLECULAR CLOUDS

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RESUMEN

Las nubes moleculares son grumosas. Gran parte de esta grumosidad no está resuelta por los telescopios de radio de un solo plato, pero es evidente en los datos de arreglos de telescopios. Aún en los datos observacionales no resueltos, la existencia de grumosidad se puede inferir a partir de la distribución de especies moleculares. Esta evidencia requiere que las especies moleculares "tempranas" estén por todas partes, mientras que las especies "tardías" estén más confinadas, y posiblemente asociadas a las estrellas recién formadas. Se requiere que los grumos sean temporales.

Los grumos moleculares también pueden observarse cerca de los objetos HH. Estos grumos tienen una composición química diferente a la de los grumos en los interiores de las nubes y su emisión de HCO^+ y NH_3 es fuerte. Estos grumos HH son dinámicamente quietos; no han sido alcanzados por el choque del objeto HH. Aqui discutimos un estudio detallado tanto observacional como teórico de un grumo HH, y mostramos que este grumo tiene que ser temporal y tener una densidad y temperatura parecidas a las de los grumos detectados o inferidos en los interiores de las nubes moleculares. Se demuestra que la química anómala es el resultado de la iluminación por el objeto HH de las regiones que de otra manera estarían obscuras, de modo tal que en estas regiones una fotoquímica significativa se desarrolla. Por lo tanto, los grumos HH probablemente son de la misma familia que los grumos en los interiores de las nubes, aunque son distintos químicamente.

Es una consecuencia de las ideas aquí presentadas que la distribución de masa de los grumos debe estar relacionada a la formación de las estrellas de baja masa.

ABSTRACT

Molecular clouds are clumpy. Much of the clumpiness is unresolved by single-dish telescopes but is apparent in the data from array telescopes. Even in the unresolved observational data, the existence of clumpiness can be inferred from the distribution of molecular species. This evidence requires that "early-time" molecular species are widespread, while "late-time" species are more confined, and possibly associated with newly formed stars. The clumps are required to be transient.

Molecular clumps may also be observed close to HH objects. These clumps have a chemical composition different from that of clumps in a cloud interior, and the emissions from HCO^+ and NH_3 are strong. These HH clumps are dynamically quiescent; they have not been overtaken by the HH shock. We discuss here a detailed observational and theoretical study of one HH clump, and show that this clump must be transient and have a similar density and temperature to those clumps detected or inferred in the cloud interior. The anomalous chemistry is shown to be the result of HH illumination of regions that would otherwise be dark, so that in these regions a significant photochemistry develops. Thus, HH clumps are probably of the same family as the clumps in cloud interiors, even though they are chemically distinct.

It is a consequence of the ideas presented here that the clump mass distribution should be related to the formation of low-mass stars.

Key Words: **ISM: JETS AND OUTFLOWS — ISM: MOLECULES**

1. CHEMISTRY IN HH-ILLUMINATED CLUMPS

It has been established over the last few years that a number of HH objects have associated with them distinct molecular clumps (Rudolph & Welch 1988, 1992; Dent et al. 1990; Girart et al. 1994, 1998, 2000, 2001; Davis, Dent, & Burnell 1990; Torrelles et al. 1992, 1994; Choi & Zhou 1997). These clumps are typically up to one tenth of a parsec from the HH objects, are dense and cool and show narrow linewidths. Evidently, they have not been shocked. They were first identified in lines of HCO^+ and NH_3; these molecules show line intensities anomalously strong compared to quiescent dark clouds. The clumps are found generally somewhat downstream of the HH jet, and are interpreted to be within the molecular cloud that the HH jet is penetrating. To account for the anomalous chem-

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istry, Girart et al. (1994) proposed that radiation generated in the HH shock triggers a photochemistry which helps to release the icy mantles on dust in the clump, and causes a photoionization that generates an active chemistry. This is summarized in the following reactions:

$$(H_2O, CO, NH_3, \dots)_{\rm ice} \rightarrow (H_2O, CO, NH_3, \dots)_{\rm gas}, \quad (1)$$

$$CO \rightarrow C \rightarrow C^+, \quad (2)$$

$$C^+ + H_2O \rightarrow HCO^+. \quad (3)$$

Taylor & Williams (1996) numerically investigated a simple model of such a process and confirmed that appreciable enhancements of HCO^+ and NH_3 should arise in the irradiated clump. Viti & Williams (1999) considered a more detailed model with a much more extended chemistry and predicted that, besides HCO^+ and NH_3, a wide range of molecular species would be expected to have abundances enhanced compared to those normally found in molecular clouds. These species included CH_3OH, H_2CO, SO, SO_2, and CN. A very detailed observational study, using BIMA and CSO, of the clump associated with HH 2 (Girart et al. 2002) measured the abundances of many molecular species in that source. In qualitative terms, the predictions of Viti & Williams (1999) agreed well with these measurements (see Table 1), and thus the general plausibility of the model proposed by Girart et al. (1994) appeared to be confirmed: the chemistry in a clump associated with (but not shocked by) an HH object is consistent with that of a dense gas in which photodesorption and photochemistry driven by the HH radiation field modify the typical chemistry of the quiescent, dark gas.

The detailed results of Girart et al. (2002) for the clump associated with HH 2 established the variation of the column density of molecular species through the clump with distance from the HH shock. These column densities rise to a peak, then fall with distance from the shock. Viti et al. (2003a) have developed a chemical model specifically for the HH 2 clump, in an attempt to determine the physical parameters of this region. This model incorporates as free parameters the clump density, the HH UV radiation field, the HH X-ray field, and the degree of freeze-out within the clump before the incidence of the HH radiation. Although this model is spatially simplistic (cf. Hester, Stapelfeldt, & Cohen 1998), Viti et al. (2003a) obtained reasonable agreement with the observational results of Girart et al. (2002).

TABLE 1

HH 2 CLUMP COLUMN DENSITIES

Molecule	Observed[a] cm^{-2}	Predicted[a] cm^{-2}
CO	3.8(17)	3.1(17)
HCO^+	1.0(13)–1.0(14)	3.0(13)
CH_3OH	6.4(13)	7.8(13)
H_2CO	5.7(13)	3.3(13)
SO	3.2(13)	3.0(13)
SO_2	1.7(13)	1.8(13)
HCN	4.1(12)	4.0(12)
CN	3.4(12)	4.0(12)
CS	2.8(12)	8.0(12)

[a] $x(y) \equiv x \times 10^y$.

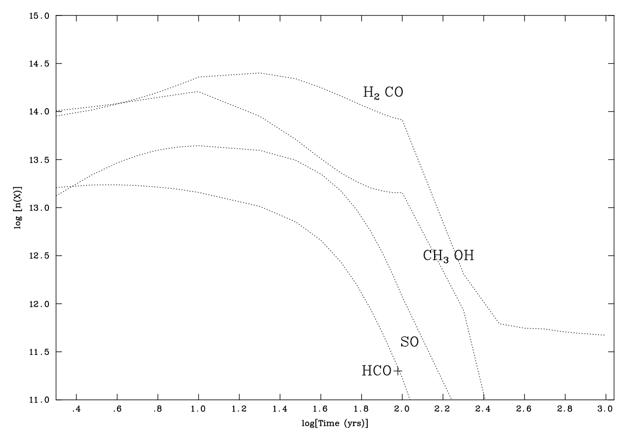

Fig. 1. Fractional abundances (relative to hydrogen) of selected species as a function of time (in log) for the best matching model of the clump ahead of HH 2. See Viti et al. (2003a) for more details.

They deduced that the X-rays did not significantly modify the chemistry, but that both the initial level of freeze-out on to dust and the UV radiation intensity were significant in determining the chemistry. Figure 1 shows the column density of selected species for the best matching model taken from Viti et al. (2003a). It is clear from this picture that the observed chemistry must be short-lived.

In fact, the initial level of freeze-out is required to be an intermediate value, corresponding to there being comparable amounts of heavy molecules being in the gas and in the ices. The implication is that the clump must be transient, otherwise at the inferred high clump density the freeze-out would be nearly total if the clump had a prolonged existence i.e., longer than a few million years. Thus, the clump survival time must be on the order of one million years. Similarly, the radiation field must be large enough to promote a prompt photochemistry, but not so large as to destroy the products of that chemistry too rapidly.

It was evident that although the Viti et al. (2003a) model was too simple to represent the complexities of the spatial situation as indicated by Hester et al. (1998), some general conclusions could be drawn from this study. These were as follows:

1. the clump has a density structure, with a peak number density of H nuclei of around $3 \times 10^5\,\mathrm{cm}^{-3}$ and an average number density one order of magnitude smaller;

2. the lifetime of the clump after irradiation begins is on the order of a hundred years, and after that molecular abundances in the clump decline;

3. the clump is probably overtaken by the HH shock front in a similar timescale;

4. the radiation field intensity incident on the clump is in the range of one hundred to one thousand times the mean interstellar intensity;

5. comparable amounts of "heavy" molecules exist in the gas and in ices on the dust, before the clump is irradiated; and

6. X ray emission from HH 2 does not appear to affect the chemistry in the clump significantly.

The question arises: what is the relation between these clumps that have been illuminated by the HH radiation and the general clumpiness that may be present in molecular clouds? We explore this in the next section.

2. CLUMPINESS WITHIN MOLECULAR CLOUDS

Single-dish observations of molecular lines in dark clouds tend to reveal relatively smooth structures. However, there are some differences between the morphologies of different species. For example, emission from the CS molecule generally traces the full extent of the cloud and shows a fairly smooth structure, but ammonia emission is generally much more confined around regions where star formation is occurring (Zhou et al. 1989; Myers et al. 1991; Pastor et al. 1991; Morata et al. 1997). This behaviour is found in many dark clouds where low-mass star formation is taking place, but it is the reverse of naive expectation. Since the critical density of the CS emission line is actually slightly larger than that of the ammonia line, CS and NH_3 should be tracing more or less the same material, or—if there is a slight difference—CS might be expected to favour the denser material that is—presumably—associated with star formation.

One interpretation of this unexpected result was given by Taylor, Morata, & Williams (1996) in terms of the effects of time-dependent chemistry. Studies of low-temperature, high-density, time-dependent chemistry, with initial atomic conditions (but most hydrogen in H_2), show that some molecules rise towards their peak values distinctly earlier than others. The "early-time" species include CS, and the "late-time species" include NH_3. Consequently, Taylor et al. (1996) suggested that molecular clouds contain density fluctuations unresolved by the single-dish observations available at that time. These density fluctuations were required to have a duration of around one million years, so that CS would reach a high abundance while that of NH_3 was still rising. These fluctuations were assumed to decay to some undetermined background density in which molecular abundances would be expected to be lower than in the density enhancements. Not all the fluctuations would be expected to be identical. Occasionally, a fluctuation might be of higher density and mass; such a fluctuation would certainly evolve faster chemically and dynamically, and may generate enough self-gravity to form a star.

In this picture, therefore, there would be a natural association of ammonia emission and star formation. The CS emission would appear wherever the unresolved density fluctuations appeared, and would therefore be a superposition of emission from many fluctuations. The CS line width would therefore be larger than that of the NH_3 which should arise in a few denser clumps. This is, in fact, observed.

Taylor et al. (1996) offered no explanation of the origin of such unresolved fluctuations, but very strong support for this model has come in the results of BIMA observations of the dark cloud L 673 (Morata, Girart, & Estalella 2002). These observations were of a small region of the cloud in lines of CS, N_2H^+, and HCO^+, and showed that the cloud is indeed clumpy on a small scale, of the order of 10 arcsec. Such clumps are indeed unresolved by conventional single-dish observations. Smaller clumps than these may also exist, but were not resolved in the BIMA observations, nor could any background molecular emission be detected. The structure detected in the three molecular species is not identical, suggesting that the clumps are transient on a timescale corresponding to the epochs at which different species peak in abundance, i.e., on the order of a million years in the chemical evolution timescale. Thus, the BIMA observations in the three molecular lines may illustrate clumps in different stages of evolution.

Therefore, for at least one cloud, L 673, the observational evidence supports the view that the cloud contains an assembly of transient clumps with lifetimes on the order of a million years. Such clumps should not show NH_3 or other late-time molecules, but only early-time molecules like CS. At least some of these clumps are resolved in the BIMA observations. Thus, the picture revealed by the observations of Morata et al. (2002) is entirely consistent with the dynamical picture suggested by Taylor et al. (1996).

3. THE ORIGIN OF THE DENSITY FLUCTUATIONS

What causes the transient clumps? Evidently, they are some kind of representation of interstellar turbulence (cf. Franco & Carramiñana 1999). However, it seems quite unlikely that they can arise in hydrodynamical processes (Hartquist, Falle, & Williams 2002) and that an MHD context is required. Falle & Hartquist (2002) have shown that under suitable conditions slow mode MHD waves can create large density enhancements, of the order of a factor of 30, and that the duration of the enhancement is on the order of 1 My. Thus, slow mode MHD waves are potential carriers of the transient density enhancements proposed by Taylor et al. (1996) and apparently observed by Morata et al. (2002). If so, then the implication from the work of Falle & Hartquist (2002) is that the ambient number density in the cloud is about 300 H nuclei cm^{-3} and that the maximum density in a fluctuation is about 10^4 cm^{-3}, as indicated by the CS observations in L 673 and other clouds.

Small-scale density fluctuations have, in fact, been detected in the diffuse interstellar medium, and it is possible that these also arise in slow mode MHD waves, excited in this case by dissipation of Rayleigh-Taylor or other instabilities at diffuse cloud boundaries (Hartquist et al. 2002). These small-scale structures have been detected in the line of sight towards pulsars and double stars, and towards single stars where the structure has a transverse motion to the line of sight. For example, in one cloud component towards δ Orionis, the strength of the Na D1 line has been observed to vary by factors of two within a period of 6 years (Price, Crawford, & Howarth 2000; Price, Crawford, & Barlow 2001). The interpretation is that small-scale structure of size about 10 AU has passed through the line of sight with a transverse velocity of about 20 km s^{-1}. Such structures must have much larger densities than the mean density in the diffuse interstellar medium.

The mechanism of Falle & Hartquist (2002) is potentially of wide application. Its application to the small-scale structures arising in diffuse clouds remains to be confirmed, but it is highly plausible that these effects are playing a significant role. If so, then viable applications may be made to explain the clumps detected (Blitz & Stark 1986; Williams, Blitz, & Stark 1995) in the Rosette Molecular Cloud—a large Giant Molecular Cloud—and also to the substructure which may be that observed by Morata et al. (2002) in L 673. The chemistry that would arise in a cloud made up of an ensemble of such transient clumps is being evaluated by Garrod et al. (2003).

4. OBSERVED HH-ILLUMINATED CLUMPS AS TRANSIENT DENSITY FLUCTUATIONS

The clumps illuminated by HH objects appear to belong to the class of structures predicted by Taylor et al. (1996) and observed by Morata et al. (2002). Assuming that the conclusions of Viti et al. (2003a) concerning the clump associated with HH 2 are generally valid, then such clumps are necessarily transient on a timescale of about 1 My, their number density is about 10^4 H nuclei cm^{-3}, and they are cool and quiescent. Their chemistry is anomalous when compared to cool clouds simply because of the effects of the HH radiation in driving a photochemistry that enhances certain species, notably HCO^+. When a clump that is normally in a near-dark environment is subjected to the UV radiation from an HH shock, it responds in a characteristic way.

We conclude that clumps illuminated by HH objects are simply members of the same class of density fluctuations distributed throughout molecular clouds. If so, then the HH objects provide a means of studying individual clumps that happen to be close to the HH shock. Localized and anomalously large HCO^+ abundances are a clear signature of this physics. A search for density enhancements by this method is under way (Viti et al. 2003b).

5. SUMMARY

There is strong evidence—both observational and theoretical—that molecular clouds are clumpy on a scale that is normally unresolved, and that most of these clumps simply dissipate into an interclump medium on a timescale on the order of 1 My. Those clumps that happen to be near an HH object are affected by its radiation field, and generate a characteristic variety of molecular species. This variety is a signature of photochemistry on a dense clump, and HH objects therefore provide a useful tool for studying molecular cloud density fluctuations through the response of these fluctuations to radiation. Although these clumps are generally too small to detect in single-dish studies, they may be readily detected in array telescope observations. The origin of these clumps is probably in slow-mode MHD waves; these waves may have other interstellar consequences, including the small-scale structure recently detected in the diffuse interstellar medium.

Clumpiness in molecular clouds is clearly of relevance to the initiation of low-mass star formation. In the picture presented here, most density fluctuations simply dissipate into the background gas, and the chemistry that they show is that of "early-time" species (Taylor et al. 1996). However, denser or more massive fluctuations may develop sufficient self-gravity to proceed to star formation. Regions associated with star formation should develop "late-time" species (Taylor et al. 1996). Thus the clump mass spectrum, a quantity that can be determined by the means discussed here, may be related to the stellar initial mass function.

The ideas presented here draw together contributions from many collaborators. We would particularly like to draw attention to the work of colleagues at UCL: R Garrod; at Barcelona: R. Estalella, J. M. Girart, and O. Morata; at Leeds: S. A. E. G. Falle and T. W. Hartquist; and at CfA: P. T. P. Ho. We are grateful to the Particle Physics and Astronomy Research Council for their support of our research.

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