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THE CHEMISTRY OF STELLAR JETS

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RESUMEN

Se pueden explorar muchos fenómenos astronómicos a través de observaciones de la emisión de líneas moleculares. En este artículo discutimos la química que da origen a los trazadores moleculares en dos escenarios asociados con la interacción de chorros estelares con las nubes moleculares. La primera situación es el ambiente de un choque de proa cerca a la cabeza de un chorro, el cual está entrando en una nube molecular. La segunda es el caso de un grumo dentro de una nube molecular, el cual se ve afectado por el campo de radiación intensa que se genera en el choque entre el chorro y la nube. En ambos casos, se pueden identificar trazadores moleculares específicos de las condiciones físicas.

ABSTRACT

Many astronomical phenomena are conveniently explored through observations of molecular line emission. In this paper, we discuss the chemistry that gives rise to molecular tracers in two scenarios associated with the interaction of stellar jets with molecular clouds. The first situation is the environment of the bow shock near the head of a jet entering a molecular cloud. The second is the case of a clump within a molecular cloud that is affected by the intense radiation field generated in the jet/cloud shock. In both cases, specific molecular tracers of the physical conditions can be identified.

Key Words: **ISM: CHEMISTRY — ISM: MOLECULAR CLOUDS — ISM: SHOCKS — STARS: JETS AND OUTFLOWS**

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1. INTRODUCTION

Molecular astrophysics is now widely used as a useful approach to the study of many astronomical situations. Molecules are formed in gas that is relatively dense (more than one hydrogen atom per cm^{-3}) and relatively cool (less than a few thousand Kelvin), and these conditions generally apply in regions where most of the mass of the interstellar gas resides. Further, each molecule has a multitude of accessible transitions and there are over one hundred molecular species that have so far been detected in the interstellar gas. Thus, it is usually possible to select a transition to observe that is effective in tracing gas at a particular density and temperature.

In recent years, the close link between chemistry and dynamics in the interstellar medium has been explored in many applications (cf. Hartquist & Williams 1998). In this article, we explore the chemistry stimulated by the violent interaction of a fast jet with a molecular cloud. We examine how this interaction causes a complex mixing to occur and show how the mixing zone is rich in tracer molecules. Further, the shock generates an intense source of radiation within the normally dark interior of a molecular cloud. The consequences of the photochemistry induced by this radiation field have been studied observationally and theoretically. We discuss the implications of these studies for the clumpiness within molecular clouds, a key parameter for low-mass star formation.

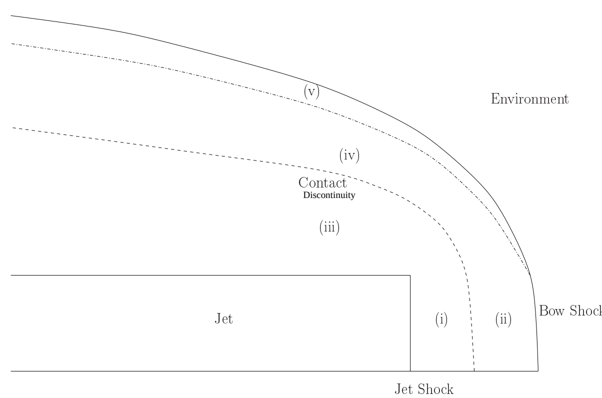

Fig. 1. Schematic diagram showing the various zones of interaction between a jet and a molecular cloud.

2. THE JET/CLOUD INTERACTION

The interaction of a stellar jet with a molecular cloud is a situation that was previously investigated theoretically by Raga et al. (1995). Their study indicated that specific chemical tracers of the various zones of interaction should be identifiable. However, although their treatment of the gas dynamics

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was very thorough, the chemical network that they used was very limited, and treated the chemistry in a rudimentary and artificial way. Here, we report preliminary results from a study by Lim, Rawlings, & Williams (2002) which uses essentially the same numerical methods as Raga et al. (1995) to describe the dynamics of the jet/cloud interaction, but which extends the chemistry very greatly. Over 100 chemical species interacting in more than 1500 chemical reactions were included in a chemistry that should represent the behaviour under all conditions likely to be achieved in the jet/cloud interaction, ranging from cold molecular cloud gas to hot shocked jet gas. There is a separate continuity equation for each species. The heating and cooling are treated conventionally, and the cooling function was that of Biro, Raga,& Cantó (1995) and Hollenbach & McKee (1979). The aim of this work is to identify tracers of the various zones of interaction (see Figure 1), which are:

(i) shocked jet gas,

(ii) shocked molecular cloud gas,

(iii) expanding shocked jet gas,

(iv) expanded shocked molecular cloud gas, and

(v) post bow-shock environment gas.

Components (i) and (ii) appear at the head of the jet, while components (iii), (iv) and (v) constitute the wake.

For the results described here, the physical parameters are as follows. The number density of hydrogen nuclei in both the jet and the molecular cloud is taken to be 100 cm^{-3}; the temperatures of the jet and cloud are 100 K and 10 K respectively, and the jet impacts on the cloud with a velocity of 50 km s^{-1}. In both the jet and the cloud, the initial chemical state is assumed to be steady-state, and the elemental abundances are taken as solar.

Figures 2a,b show the density and temperature structure arising from the jet/cloud interaction. The number density of gas between the two shocks (in the jet and in the cloud) is enhanced by a factor of 10^2 to about 10^4 cm^{-3}. At such high densities, this gas cools rapidly to low temperatures, as indicated in Figure 2b. The jet itself, however, is surrounded by low density, high temperature sheath of shocked jet gas that cools slowly. Thus, the jet remains a distinct, isolated, feature (at least, during this phase of evolution). Outside this sheath lies a more extended wake of expanding shocked molecular cloud gas in which the density is higher than ambient ($n \sim 200$–300 cm^{-3}); this gas cools through H_2 emission to $\sim 10^2$ K. Different molecules highlight the various regions of the bowshock and wake. For example, the molecular ion CH^+, known to trace warm regions of interstellar space, is abundant in the two shocks near the jet head; it is enhanced at the warm low density sheath of the jet and at the weak shock where the expansion of the wake into the ambient gas is occurring. A quite similar structure is seen in HCO^+, illustrated in Figure 2c; here, HCO^+ is abundant in the strong shocks at the jet head, and the flow from that region throughout the wake is clearly evident. Atomic carbon (Fig. 2d), however, avoids the shocks and wake regions, as it is rapidly converted into hydrocarbons and other species in warm gas. Thus, atomic carbon and HCO^+ are almost exact opposites of each other in their tracing of the jet/cloud interaction. For a full description of the chemical tracers of a jet/cloud interaction, the reader is referred to Lim et al. (2002).

Finally, we note that column densities through the interaction region are often at a level that should be detectable. For example, the number density of HCO^+ throughout much of the wake region is around 10^{-4} cm^{-3}, generating column densities on the order of 10^{11} cm^{-2}. Such column densities of HCO^+ have been detected in absorption against distant quasars (Lucas & Liszt 1996), and HCO^+ is routinely detected in cold interstellar clouds and star-forming cores. The unique thermal signature of the jet/cloud interaction should be apparent in the line profiles.

3. PHOTOCHEMISTRY INITIATED BY RADIATION FROM HERBIG-HARO OBJECTS

There is evidence for regions of enhanced molecular emission associated with Herbig-Haro objects (Rudolf & Welch 1988; Torrelles et al. 1992, 1993; Girart et al. 1994, 1998). These regions were first observed in lines of HCO^+ and NH_3. These are small, around 0.1 pc in diameter, cool and quiescent, and share the velocities of the molecular cloud rather than of the HH object (see Figure 3). The proposed origin (Girart et al. 1994) is that the intense radiation field generated in the shocked gas that is the HH object promotes a photochemistry in a dense clump of gas within the molecular cloud. This scenario is illustrated schematically in Figure 4. This proposal was first investigated by Taylor & Williams in 1996. They showed that detectable abundances of HCO^+ and NH_3 should indeed arise from a warming and evaporation of ice mantles assumed to exist on dust

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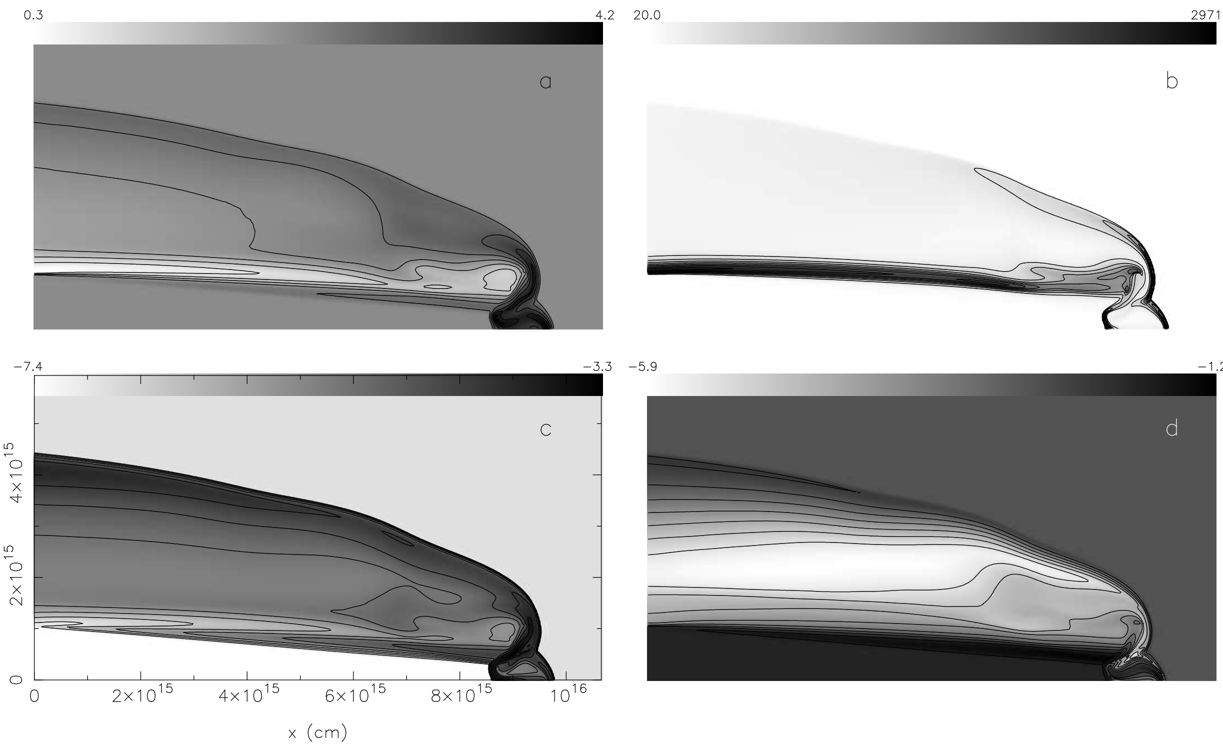

Fig. 2. The interaction of a jet ($n_H = 100$ cm^{-3} and temperature 100 K) impinging at 50 km s^{-1} on a cloud ($n_H = 100$ cm^{-3} and temperature 10 K); distributions of (a) total number density; (b) temperature; (c) HCO^+ number density; and (d) atomic carbon number density.

inside the dense clump. This evaporation liberates H_2O, CO, and NH_3 into the gas phase. The radiation from the HH object is supposed to dissociate the CO and ionize the carbon to produce C^+ which then reacts with H_2O to give HCO^+.

A more complete treatment has been given by Viti & Williams (1999). In that work, the chemistry was extended to include 119 species interacting in 1728 reactions. The formation of the clump was described as the gravitational collapse of a region of the cloud, with gas-phase chemistry and freeze-out of gas phase species on to the dust occurring during the collapse. Thus, the composition of the deposited ice was determined self-consistently with the gas-phase chemistry. Further, several surface reactions were included in the scheme, including the formation of methanol from CO. The work of Viti and Williams has indicated that a rich chemistry should arise as a result of the photoprocessing of evaporated ice material, and that these effects should be evident as anomalous abundance variations within the cloud for some 10^4 years after irradiation starts. Their work predicted that hydrocarbons such as C_3H_4, hydrogenated products of CO such as H_2CO and CH_3OH, and sulphur-bearing species such as H_2S, H_2CS, NS, SO, and SO_2 should be detectable.

A search has been made by Girart et al. (2001) using the CSO and BIMA facilities in the molecular clump associated with the Herbig-Haro object HH2, and a large number of species were detected on-source, with no detection being made off-source. The detected species include those in the general study of Viti & Williams. Hence, it seems clear from the observations that some special process is driving the chemistry in this chemically-rich clump within the molecular cloud. The column densities of the detected species in the clump associated with HH 2, calculated on the basis of local thermodynamic equilibrium, are given in Table 1.

No attempt has yet been made to match the generic model of Viti & Williams to the detections made for the source HH 2 by Girart et al. It is to be expected that the chemistry will differ as the physical parameters of the clump and those of the HH radiation field differ from source to source. Clearly, the chemical model needs to be extended to include deuterated species. Observations in progress (Girart, private communication) seem to suggest that the chemistry of clumps associated with HH objects varies considerably from object to object. This vari-

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TABLE 1

MOLECULES IN THE HH 2 CLUMP

Molecule	Column density[a]
CO	3.0×10^{17}
$C^{18}O$	4.6×10^{14}
H_2CO	1.6×10^{13}
SO	5.4×10^{13}
SO_2	$2.6–7.7 \times 10^{13}$
CH_3OH	4.2×10^{13}
HCO^+	4.2×10^{13}
HCN	4.0×10^{12}
CS	2.4×10^{12}
CN	$\sim 9.4 \times 10^{11}$
DCO^+	5.5×10^{11}
HCS^+	$< 4.0 \times 10^{11}$
DCN	$< 1.3 \times 10^{12}$
HC_3N	$< 1.7 \times 10^{12}$
H_2CS	$< 3.6 \times 10^{12}$
NS	$< 5.1 \times 10^{12}$
C_3H_2	$< 5.3 \times 10^{12}$
HCOOH	$< 6.0 \times 10^{12}$
OCS	$< 1.1 \times 10^{13}$
H_2S	$< 1.8 \times 10^{14}$

[a]Units of cm^{-2}, calculated under the assumption of LTE.

ation may be useful, in conjunction with the models, in establishing local physical parameters for the molecular cloud.

If the model proposed by Girart et al. (1994) is indeed correct, then one may expect time-dependent chemical and morphological effects to occur as the HH object moves past the clumps. This situation has been explored by Raga & Williams (2000). The HH radiation source creates an active photochemical zone on the near-side of the clump, but as the HH object moves onwards, different parts of the clump are activated, and the photochemical zone attempts to follow the motion of the HH object. However, this activation lags behind the motion of the HH object. What is actually observed depends on the orientation of the clump, and the radiation source, and the line of sight. Arc-like structures may be produced when a clump is viewed orthogonal to the HH-clump direction, but these may appear as a single "blob" when viewed along that direction. Raga & Williams attempted, unsuccessfully, to relate the rather limited information on observed morphology of clumps in molecular clouds with the known motion of HH

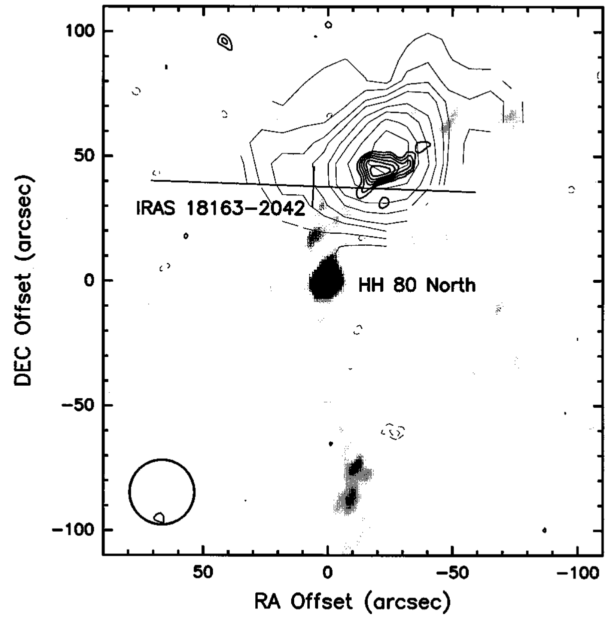

Fig. 3. HCO^+ and NH_3 contours in HH80N (taken from Girart et al. 1998)

objects. This tool to explore intimate geometries within molecular clouds remains to be developed.

One model of molecular clouds is of dense clumps at various stages of chemical and dynamical evolution, embedded in a less dense environment. As has been shown in the section, HH objects could act as useful probes of this clumpy structure within clouds: the irradiation of clumps within the cloud by HH objects creates a special photochemistry that is distinct from the chemistry in the ambient less dense environment. In principle, therefore, it should be possible to estimate the clumpiness of molecular clouds from a sufficiently detailed statistical picture of HH clumps. As yet, the information on such HH-illuminated clumps is sparse; however, Taylor & Williams (1996) were able to infer that clump sizes should be comparable with interclump distances.

Some of these clumps may be massive enough to collapse and form stars, while others may be dissipated by nearby star-formation. Such a picture of molecular clouds as dynamical entities in which clumps are continually formed and destroyed was developed by Taylor et al. (1996) to describe the gross distribution of NH_3 and CS within star-forming molecular clouds.

4. CONCLUSION

Molecular astrophysics offers an opportunity to describe in detail the interaction of a jet with a

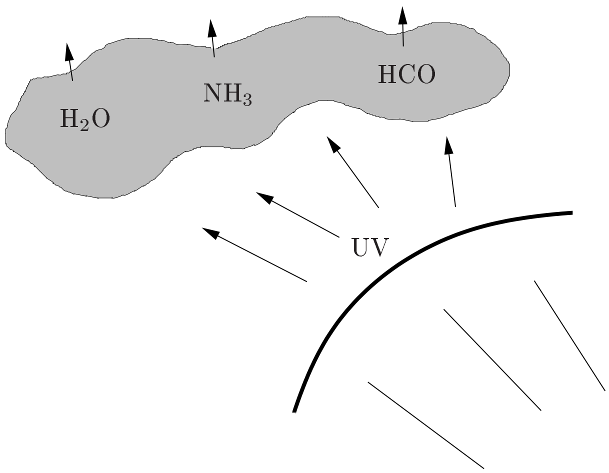

Fig. 4. Schematic illustration of the illumination of a dense clump within a molecular cloud by UV radiation (arrows) generated by the shock (thick line) caused by the impact of a stellar jet (continuous lines from the bottom of the diagram) on the molecular cloud.

molecular cloud. Detectable abundances of various species should trace the bow shock and wake.

The HH objects may be a useful tool to investigate the clumpiness of molecular clouds, an important consideration in the early stages of star-formation. The photochemistry induced by the radiation from a HH object creates a transient and time-dependent photochemical zone that shows chemical abundances that are anomalous compared to quiescent molecular clouds.

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