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Ionization structure and a critical visual extinction for turbulent supported clumps

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Abstract. We show that the fractional ionization in a wide range of models of cloud chemistry undergoes a steep decline at extinctions of $A_{\rm V} \simeq 2-3$. We identify this extinction with the critical value for clumps in the Rosette Molecular Cloud: clumps with $A_{\rm V}$ above ~ 3 may contain embedded stars, while those with extinction below this value do not. We argue that the ionization decline at this critical extinction is directly related to the extent of turbulent support in the cloud. This leads us to investigate for the first time the chemical evolution of a cloud that is initially magnetically supported against collapse perpendicular to the field lines, but is collapsing along the field lines in a 1-D mode, up to an unknown but critical density. The fractional ionization corresponding to this critical density then allows ambipolar diffusion to control a collapse across the large-scale magnetic field as well as parallel to it. The results of the chemical evolution of a cloud undergoing this two-stage collapse are presented, and are shown to be sensitive tracers of the details of the collapse mode.

Key words: molecular processes – stars: formation – ISM: abundances; clouds; magnetic fields; molecules

1. Introduction

In their work on the clumpy structure of the Rosette Molecular Cloud (RMC), Williams, Blitz and Stark (1995) identified seven star forming clumps, none of which has an estimated ^{13}CO column density, N(^{13}CO), of less than 10^{16} cm^{-2}. From their Fig. 21, it appears that eight or nine other clumps have N(^{13}CO) $> 10^{16}$ cm^{-2} but contain no stars. The estimated values of N(^{13}CO) for the star forming clumps, with one exception, vary by only a factor of about 2, and the estimated masses vary by a factor of about 7. While one could argue that the Williams et al. (1995) data point to the existence of a minimum *mass* required for star formation to occur in the RMC, we suggest that they indicate, at least as strongly, the existence of a minimum *column density*, N(^{13}CO) $\simeq 10^{16}$ cm^{-2}, for stars to be born.

Hartquist et al. (1993) suggested that there should be a maximum value of the visual extinction, $A_{\rm V}$, of a clump supported against gravitational collapse along its large-scale magnetic field by internal Alfvén waves thought to comprise clump turbulence (Arons & Max 1975; Caselli & Myers 1995; Mouschovias & Psaltis 1995). Their idea was that above this critical visual extinction the damping rate of waves by ion-neutral friction (Kulsrud & Pierce 1969) is too rapid for the waves to be maintained at sufficient amplitudes to support a clump. This damping rate of waves in which the ion-neutral motions are well-coupled declines with extinction because it increases as the inverse of the number density of ions, n_i, (and proportionally to the square of the frequency). The value of n_i itself decreases with visual extinction. Recent numerical simulations of wave behaviour in self-gravitating clumps show that nonlinear magnetohydrodynamic waves can, in fact, support such clumps against collapse (Gammie & Ostriker 1996). In view of its relevance to wave damping in clumps it is now particularly timely to return to the issue of the behaviour of $x_i \equiv n_i/n_{\rm H}$ (where $n_{\rm H}$ is the number density of hydrogen nuclei) as a function of $A_{\rm V}$.

The view taken by Hartquist et al. (1993) and by us in the current work, is, thus, that much of the molecular material in giant molecular clouds is translucent to radiation and that photoionization affects its fractional ionization, which in turn plays a role in determining the rate at which material collapses. Our view is one that has much in common with that adopted by McKee (1989) who argued that star formation regulates itself because the births of stars lead to the production of radiation which raises the fractional ionization in translucent material and, consequently, lowers the rate of ambipolar diffusion. There are differences between McKee's and our points of view. We stress the role of turbulent support of clumps like those identified by Williams et al. (1995) (see also Bertoldi & McKee 1992); these are much more tenuous objects than the magnetically subcritical dense cores in which turbulent support is likely to be much less important than the support provided by the large-scale magnetic field and in which the collapse timescale is established by ambipolar diffusion. Consequently, we feel that McKee's (1989) considerations are likely to be of more relevance to more evolved objects formed through the collapse of the sorts of clumps Williams, Blitz & Stark (1995) found in their CO studies. In this paper we do present results for the fractional ionization for a wide variety of conditions; so many of our ion-

Send offprint requests to: D.P. Ruffle ization calculations are of direct relevance for the application of McKee's (1989) model to self-regulation of later stages of the formation of low-mass stars.

Another reason for returning to this issue is that in the last few years a revision of ideas about the fractional ionization in some molecular cloud environments has occurred. Pineau des Forêts et al. (1992) and Le Bourlot et al. (1993a) discovered, for a range of assumed H_3^+ dissociative recombination rate coefficients, a class of dark cloud gas phase chemical equilibrium solutions in which the H_3^+ abundance is much lower and x_i much higher than in the solutions of the previously known class. Shalabiea & Greenberg (1995) have studied the effects on the existence of solutions belonging to the two classes of the assumed gas phase elemental fractional abundances of sulphur, $x_{\rm S}$, and low ionization potential metals, $x_{\rm M}$, such as sodium and magnesium, and of the assumed nature of grain surface chemistry modifications to the dark cloud gas phase chemistry. Though Le Bourlot et al. (1993b) and Flower et al. (1994) gave the fractional abundance of C^+, $x(C^+)$, relative to hydrogen nuclei as a function of $A_{\rm V}$ for one cloud model with an assumed radiation field like that of the typical interstellar background field, there has been no exploration of the simultaneous dependence of the fractional ionization x_i on $A_{\rm V}$, $n_{\rm H}$ (the number density of hydrogen nuclei), $x_{\rm S}$, $x_{\rm Si}$ and $x_{\rm M}$. The results of Le Bourlot et al. (1993b) and of Flower et al. (1994) indicate a transition at translucent depths for a model cloud in which $n_{\rm H}$ = 10^3 cm^{-3} from a solution of the high ionization class to one of the low ionization class.

In Sect. 2 of this paper we report the results of such an exploration and identify a variety of situations under which -d(log x_i)/d$A_{\rm V}$ is large. In Sect. 3 we give results for the chemical evolution of a parcel of gas collapsing from $n_{\rm H}$ = 10^3 cm^{-3} with an initial $A_{\rm V}$ within the range in which -d(log x_i)/d$A_{\rm V}$ is large. In our description of the collapse dynamics we include a plane parallel collapse phase, representing collapse along the field lines, followed by a phase during which the collapse takes place both across and along the large scale magnetic field and is regulated by ambipolar diffusion, the rate of which depends on the fractional ionization which is taken from our calculations.

2. Fractional ionization as a function of $A_{\rm V}$, $n_{\rm H}$, $x_{\rm S}$, $x_{\rm Si}$ and $x_{\rm M}$.

Fig. 1 contains the results of steady state equilibrium chemical models for x_i as a function of $A_{\rm V}$, the visual extinction to the near edge of a semi-infinite plane-parallel cloud. Equilibrium results were obtained through the integration of rate equations from a time when all elements more massive than hydrogen were primarily in neutral and ionic atomic form but most of the hydrogen was in H_2. The standard interstellar radiation background was assumed to be incident on the near side of the cloud, and it is assumed that a cosmic ray induced radiation field is present throughout the cloud (Prasad & Tarafdar 1983). In addition to an extensive network of gas phase reactions for which rate coefficients were taken primarily from the UMIST compilation (Millar et al. 1997), we included modifications to

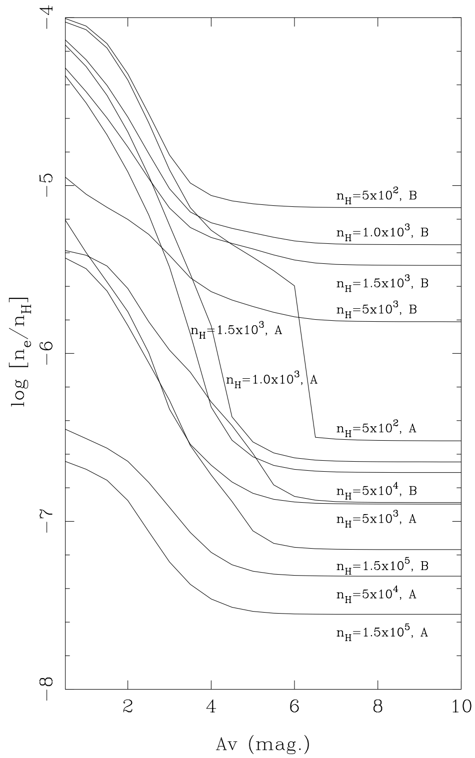

Fig. 1. Steady state fractional ionization as a function of $A_{\rm V}$, $n_{\rm H}$, $x_{\rm S}$, $x_{\rm Si}$, $x_{\rm M}$

the gas phase chemistry due to the presence of grains by assuming that all material striking grains is immediately returned to the gas phase, but that many of the species are processed in such a way that much of the material is returned in the form of saturated species like H_2, NH_3, H_2S and CH_4. The detection of NH in interstellar clouds (Meyer & Roth 1991; Crawford & Williams 1997) supports this view, at least for clouds with values of $A_{\rm V} \sim 1$ (see Williams 1993). The rate at which particles of neutral species X were assumed to strike grain surfaces is 3.5 $\times$ 10^{-18} s^{-1} (m$_{\rm X}$/amu)$^{-1/2}$ ($n_{\rm H}$/cm^{-3}), where $n_{\rm H}$ is the number density of hydrogen nuclei; charged particles were assumed to strike grains (mostly negatively charged) at a rate that is 18 times larger (following Rawlings et al 1992). All ions striking grains were assumed to return to the gas phase as neutral atoms and molecules. The cosmic ray ionization rate was taken to be 1.3×10^{-17} s^{-1}. Molecular hydrogen is self-shielding, and CO was assumed to be sufficiently self-shielded and shielded by H_2 that only photons produced as a consequence of cosmic ray induced ionization are important for its photodissociation.

The results in Fig. 1 are for the two sets of assumed gas phase elemental abundances given in Table 1 (see Shalabiea & Greenberg 1995). Set A is similar to that required in many cases to reproduce chemical abundances measured for dark cores while Set B, which has higher fractional abundances of low ionization potential elements, is selected because diffuse clouds have much higher gas phase fractional abundances of those species than dark cores. The issue of the mechanisms that control the depletion of the low ionization elements is unclear at present

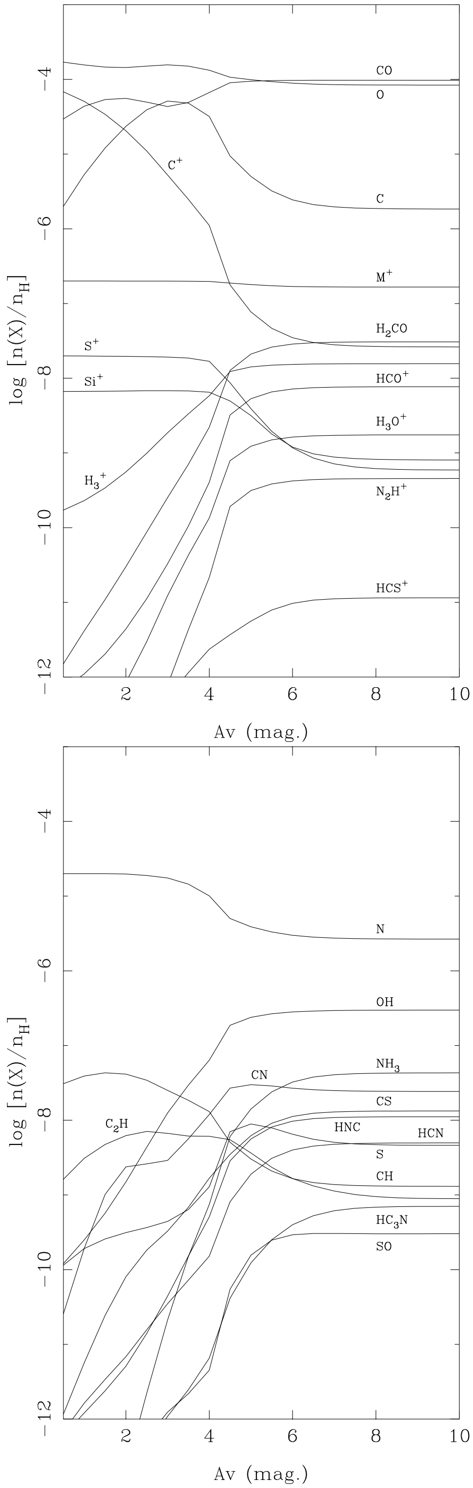

Fig. 2. Steady state fractional abundances of species as functions of $A_{\rm V}$ for $n_{\rm H}$ = 10^3 cm^{-3} and case A depletions (see text for description)

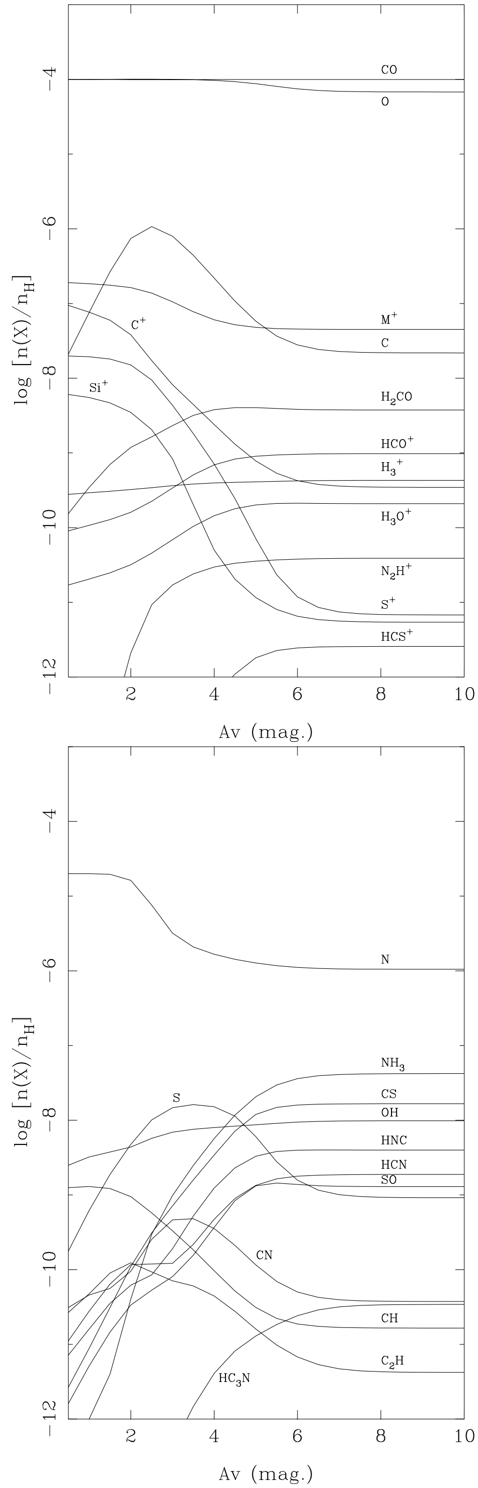

Fig. 3. Steady state fractional abundances of species as functions of $A_{\rm V}$ for $n_{\rm H}$ = 5×10^4 cm^{-3} and case A depletions (see text for description)

(hence the parametrised approach adopted here), but is one of major importance for the chemistry of star formation, as the results in this paper indicate.

Inspection of Fig. 1 shows that for $n_{\rm H}$ = 5×10^2 cm^{-3} (typical of the RMC clumps) the gradient -d(log x_i)/d$A_{\rm V}$ reaches a maximum in the range $A_{\rm V} \approx 2 - 3$ for Set B depletions and a local maximum for the same range of $A_{\rm V}$ for Set A depletions. For Set A depletions and $n_{\rm H}$ = 500 cm^{-3} a much higher value of -d(log x_i)/d$A_{\rm V}$ exists for a very small range of high values of $A_{\rm V}$ where a chemical phase transition occurs, but the high value

Table 1. Fractional elemental abundances relative to $n_{\rm H}$

	A "dark"	B "diffuse"
He	7×10^{-2}	7×10^{-2}
C	1×10^{-4}	1×10^{-4}
N	2×10^{-5}	2×10^{-5}
O	2×10^{-4}	2×10^{-4}
S	2×10^{-8}	3×10^{-6}
Si	7×10^{-9}	1×10^{-6}
M	2×10^{-7}	1×10^{-6}

of -d(log x_i)/d$A_{\rm V}$ in the range of $A_{\rm V} \approx 2 - 3$ Set A as well as Set B depletions, is no doubt important for the ion-neutral damping of turbulence supporting RMC-like clumps. Taking (1 $\times$ 10^{16} cm^{-2}/2) to be half the critical measured value of the ^{13}CO column density from the edge of an RMC clump to its centre, $n(^{13}{\rm CO})/n_{\rm H}$ = 1 $\times$ 10^{-6} (Williams et al. 1995), and the standard conversion of the hydrogen nuclei column density to $A_{\rm V}$ (Savage & Mathis 1979), we find that the critical visual extinction from the centre of an RMC clump to its edge is 2.5, in agreement with the regime of maximum -d(log x_i)/d$A_{\rm V}$ for $n_{\rm H}$ = 500 cm^{-3} identified in our calculations.

Results for x_i are also given in Fig. 1 for a range of values of $n_{\rm H}$. As stated above, the ion-neutral damping rate of a wave of sufficiently low frequency is proportional to the square of the wave frequency divided by n_i. A comparison of the Set A graphs for $n_{\rm H}$ = 5 $\times$ 10^2 cm^{-3} and $n_{\rm H}$ = 5 $\times$ 10^4 cm^{-3} shows that at $A_{\rm V}$ = 3, the values of n_i for the two model clumps are roughly equal. Therefore the ion-neutral wave damping rate for a given frequency has roughly the same functional dependence on $A_{\rm V}$, implying that even for dense cores the $A_{\rm V}$ dependence of x_i must be taken into account in any consideration of wave propagation.

The chemical calculation yielding x_i also provides information about the depth dependence of many other chemical abundances. Figs. 2 and 3 give results for the fractional abundances of a number of species for a $n_{\rm H}$ = 1 $\times$ 10^3 cm^{-3}, Set A clump and a $n_{\rm H}$ = 5 $\times$ 10^4 cm^{-3}, Set A dense core. The model results indicate that other than CO emissions only CH and OH emissions are likely to be detectable towards RMC clumps with $n_{\rm H}$ = 1000 cm^{-3}, and also that the CH, OH and CO fractional abundances are not sensitive to $x_{\rm S}$, $x_{\rm Si}$ and $x_{\rm M}$. Unfortunately, values of CH and OH abundances are difficult to infer observationally. A comparison of Fig. 3 with Fig. 2 shows that M^+ is the dominant ion throughout a dense core, while C^+ is the dominant ion over a large range of $A_{\rm V}$ in $n_{\rm H}$ = 1000 cm^{-3} gas. Unlike RMC-type clumps with $A_{\rm V}$ = 3, a dense core with $A_{\rm V}$ = 3 and $n_{\rm H}$ = 5 $\times$ 10^4 cm^{-3} is likely to produce observable emissions in a number of molecular species other than CH, OH and CO, including HCO^+, N_2H^+, H_2CO, CN, NH_3, CS and possibly HNC and HCN.

Though our results are more extensive than those of previous authors, they are in harmony with those of Le Bourlot et al. (1993b), Flower et al. (1994), and Shalabiea & Greenberg (1995) in regions where comparisons can be made.

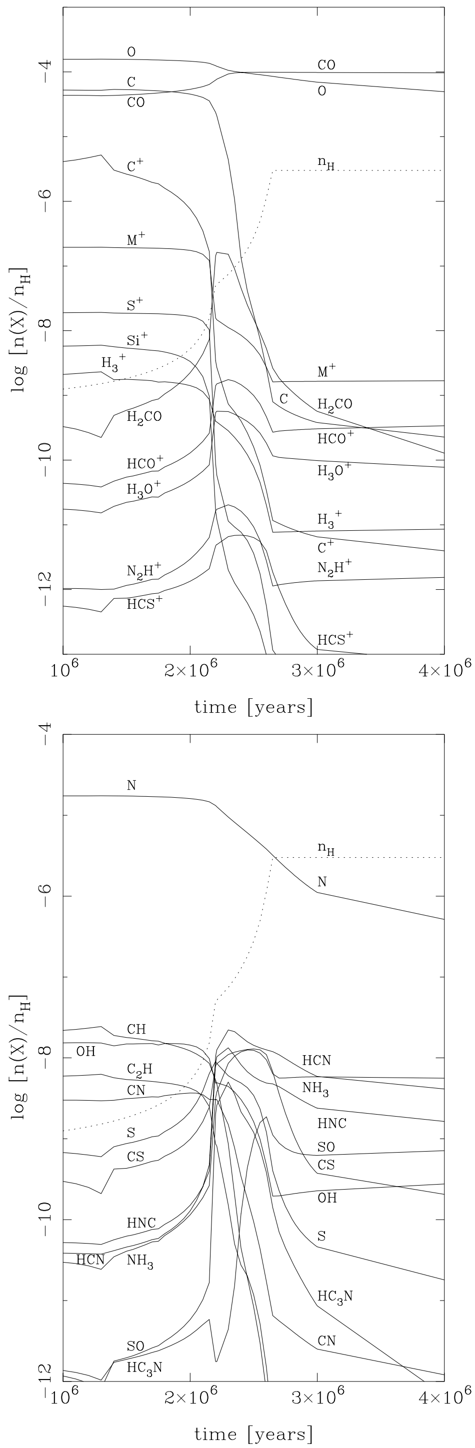

Fig. 4. Fractional abundances as functions of time since the onset of collapse for model 1 ($n_{\rm Hc}$ = 2 $\times$ 10^4 cm^{-3}). The dashed curves give ($n_{\rm H}/10^{12}$ cm^{-3})

3. Collapse from $A_{\rm V}$ = 3

We propose that $A_{\rm V} \approx$ 2.5 to 3.0 represents a critical range for the stability of RMC-type clumps. Above this critical range, the level of ionization and hence the level of turbulent support both fall. We do not know what mechanism is most effective

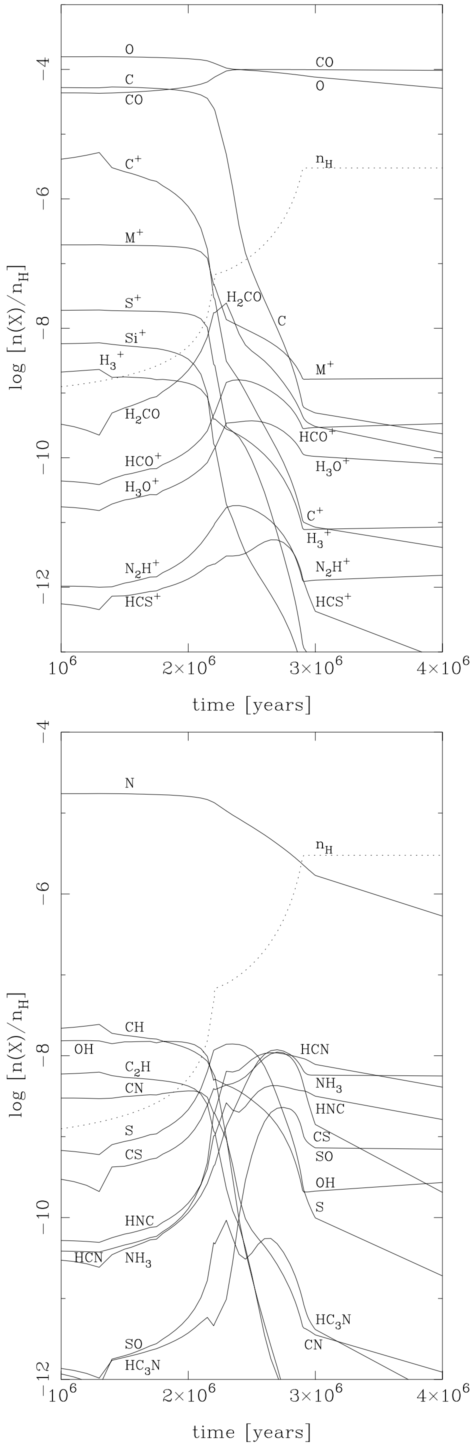

Fig. 5. Fractional abundances as functions of time since the onset of collapse for model 2 ($n_{\rm Hc}$ = 6 × 10^4 $\rm cm^{-3}$). The dashed curves give ($n_{\rm H}/10^{12}$ $\rm cm^{-3}$)

in increasing the extinction of a clump so that it is in or above this critical range, but various possibilities exist. These include compression by clump-clump collisions and increases in the interclump pressure caused by stellar winds or a supernova (e.g. Hartquist & Dyson 1997). In any case, in our study of the time dependent dynamics and chemical evolution of the centre of a collapsing clump, initial chemical conditions like those obtaining at $A_{\rm V}$ = 3 in the $n_{\rm H}$ = 1000 $\rm cm^{-3}$ Set A model of the previous section may be reasonably realistic. Thus, we have adopted such initial conditions for two models of collapsing clumps, and in this section we describe the chemical evolution of a parcel of gas during the collapse phase, in a more realistic but simple version of cloud collapse. At this time our contention that a value between 2.5 and 3 for $A_{\rm V}$ is a critical one may be viewed as being based on a plausibility argument requiring a more rigorous demonstration through numerical MHD studies of the responses of turbulent clumps to perturbations. In any case, the RMC clumps are translucent and dense cores form in the collapse of such objects. Thus, the results of this section are relevant to clump collapse and core formation and evolution and should be considered to be for initial conditions that not only differ from those used previously in investigations of chemistry during collapse but are also more representative of the chemical state in a typical RMC clump.

In each model, collapse was initially taken to be one-dimensional so that $A_{\rm V}$ remains at a constant value of 3. Such a collapse at constant $A_{\rm V}$ is an approximation to the type of collapse found to occur initially along the magnetic field in numerical simulations of the evolution of a cloud in which the magnetic pressure initially is by far the highest pressure (Fiedler & Mouschovias 1993). The density was taken to be that which results from the collapse from rest of a plane-parallel cloud with a column density of hydrogen nuclei of 10^{22} $\rm cm^{-2}$ and an initial value of $n_{\rm H}$ of 10^3 $\rm cm^{-3}$, until $n_{\rm H}$ reaches a critical value, $n_{\rm Hc}$. For the results in Fig. 4, $n_{\rm Hc}$ = 2 × 10^4 $\rm cm^{-3}$ (model 1); for model 2 (see Fig. 5), we set $n_{\rm Hc}$ = 6 × 10^4 $\rm cm^{-3}$. After $n_{\rm H}$ = $n_{\rm Hc}$, collapse was taken to occur at a rate slower than the spherical free-fall timescale by a factor of 6.95(n_i/10^{-3} $\rm cm^{-3}$)$(n_{\rm H}/n_{\rm Hc})^{-1/2}$, in harmony with the object being magnetically subcritical and subsequent collapse taking place at a rate controlled by ambipolar diffusion (Mouschovias 1987). For $n_{\rm H} > n_{\rm Hc}$ we set

$$A_V = 0.5 + 2.5 \left(\frac{n_{\rm H}}{n_{\rm Hc}} \right)^{2/3} \quad (1)$$

in our models, where an interclump medium was assumed to be responsible for the constant contribution to the $A_{\rm V}$. For the purposes of our calculation we assume that the collapse halts at a density of 3 × 10^6 $\rm cm^{-3}$, after which the cloud is treated to be static. The models use the grain-modified gas phase chemistry as described in the previous section. Note that this implies that freeze-out is off-set by chemically driven desorption. Results are given for both models in Table 2, where t_1 and t_2 are the times since collapse began in the cases $n_{\rm Hc}$ = 2 × 10^4 $\rm cm^{-3}$ (model 1) and the $n_{\rm Hc}$ = 6 × 10^4 $\rm cm^{-3}$ (model 2), respectively. Here, x_1(X) and x_2(X) denote the fractional abundance of species X relative to $n_{\rm H}$ in the two models, where *i* represents ions. These exploratory calculations of chemical evolution are the first in which the initial collapse is plane parallel along the field lines, setting up conditions for multidimensional collapse modulated realistically by ambipolar diffusion.

Table 2. Fractional abundances as functions of $n_{\rm H}$ for two collapse models

$n_{\rm H}$ (cm^{-3})	2×10^4	7×10^4	2×10^5	5×10^5
t_1 (10^6yr)	2.15	2.30	2.45	2.55
t_2 (10^6yr)	2.15	2.21	2.60	2.75
x_1(CO)	6.399(−05)	9.277(−05)	9.830(−05)	9.875(−05)
x_2(CO)	6.399(−05)	7.661(−05)	9.963(−05)	9.948(−05)
x_1(CH)	8.577(−09)	8.711(−10)	1.919(−11)	3.025(−12)
x_2(CH)	8.577(−09)	5.538(−09)	4.828(−12)	7.387(−13)
x_1(OH)	9.808(−09)	4.442(−09)	2.322(−09)	9.937(−10)
x_2(OH)	9.808(−09)	5.144(−09)	2.105(−09)	1.049(−09)
x_1(CN)	3.077(−09)	1.504(−09)	1.816(−10)	4.394(−11)
x_2(CN)	3.077(−09)	1.928(−09)	4.441(−11)	1.923(−11)
x_1(CS)	2.456(−09)	1.101(−08)	1.271(−08)	1.261(−08)
x_2(CS)	2.456(−09)	3.813(−09)	9.366(−09)	1.088(−08)
x_1(SO)	5.854(−12)	4.404(−12)	4.399(−10)	1.587(−09)
x_2(SO)	5.854(−12)	4.987(−12)	1.538(−09)	2.303(−09)
x_1(C_2H)	2.510(−09)	1.523(−10)	2.020(−11)	5.211(−12)
x_2(C_2H)	2.510(−09)	1.118(−09)	3.554(−12)	6.780(−13)
x_1(H_2CO)	7.316(−09)	1.519(−07)	2.498(−08)	9.245(−09)
x_2(H_2CO)	7.316(−09)	1.743(−08)	3.120(−09)	1.437(−09)
x_1(HNC)	4.001(−10)	1.335(−08)	6.744(−09)	5.262(−09)
x_2(HNC)	4.001(−10)	1.039(−09)	4.060(−09)	4.159(−09)
x_1(HCN)	4.762(−10)	2.218(−08)	1.585(−08)	1.332(−08)
x_2(HCN)	4.762(−10)	2.020(−09)	1.067(−08)	1.057(−08)
x_1(NH_3)	2.646(−10)	8.574(−09)	1.253(−08)	1.148(−08)
x_2(NH_3)	2.646(−10)	4.505(−10)	1.042(−08)	1.145(−08)
x_1(HC_3N)	1.668(−11)	5.036(−09)	1.631(−09)	7.510(−10)
x_2(HC_3N)	1.668(−11)	4.723(−11)	5.500(−11)	3.724(−11)
x_1(M^+)	1.212(−07)	4.376(−08)	6.948(−09)	4.368(−09)
x_2(M^+)	1.212(−07)	1.366(−08)	9.742(−09)	7.768(−09)
x_1(C^+)	1.681(−07)	7.368(−10)	2.645(−10)	8.348(−11)
x_2(C^+)	1.681(−07)	2.786(−08)	3.048(−10)	8.494(−11)
x_1(S^+)	1.035(−08)	1.144(−11)	5.705(−12)	1.764(−12)
x_2(S^+)	1.035(−08)	2.649(−09)	2.931(−11)	3.127(−12)
x_1(i)	3.095(−07)	1.480(−08)	9.122(−09)	5.345(−09)
x_2(i)	3.095(−07)	7.790(−08)	8.915(−09)	5.330(−09)

Note that the chemically driven desorption of unsaturated species are here assumed to eject *all* molecules arriving at grain surfaces (see Williams & Taylor 1996), so that the abundances in Figs. 4 and 5 are not constrained by freeze-out. Consequently, the late-time peaks in hydrocarbons and related species (Ruffle et al. 1997) are not evident. In fact, the results in Figs. 4 and 5 are similar in character to those of Howe et al. (1996) who showed that reasonable fits to the chemistry in cores A-D of TMC-1 could be obtained if a low effective freeze-out rate is assumed.

In Table 2, the calculated fractional abundances when the collapse has attained a density of $n_{\rm H}$ = 2 × 10^4 cm^{-3} of all species are the same for both models. At this point the two models have yet to diverge. After this point, the fractional ionization in model 1, in which the plane-parallel collapse at constant $A_{\rm V}$ occurs until $n_{\rm Hc}$ = 2 × 10^4 cm^{-3}, is lower than in model 2 where $n_{\rm Hc}$ = 6 × 10^4 cm^{-3}. This is a consequence of the visual extinction being lower in model 2, leading to the background interstellar photons continuing to be important for longer than in the model 1. This leads to a suppression by photodissociation of the early-time peaks of some species in model 2, which do exhibit an early-time peak in model 1. In addition, greater amounts of C, C^+ and O^+ occur in model 2 than in model 1 at $n_{\rm H}$ = 7 × 10^4 cm^{-3}. However, one may account for the timescale difference between the two models, in that model 2 reaches the density of $n_{\rm H}$ = 7 × 10^4 cm^{-3} earlier than model 1 and then reaches the following displayed density of $n_{\rm H}$ = 2 × 10^5 cm^{-3} at a later time than model 1.

The late-time abundances of early-time species are reduced in model 2, as a result of the lower visual extinction at $n_{\rm H}$ = 2 × 10^5 cm^{-3}, and the longer time that model 2 takes to reach that density. However, NH_3, SO and CS are seen to still be increasing in abundance in model 2, whilst in model 1 their abundances have already peaked.

Recently Ruffle et al. (1997) have argued that the abundances of HC_3N and C_2H will rise at late times in dense cores as depletion occurs; Caselli et al. (1998) have even used the measured fractional abundances of HC_3N in numerous cores to infer the depletions, relative to solar abundances, of C, N and O on the assumption that they did not vary from element to element. Ultimately to establish reliably that depletion is usually the cause of high abundances of such putative early-time molecules, considerable data about the abundances of species with abundances that are sensitive to the relative depletions of trace elements must be gathered. Our current results show that for cores in which high fractional abundances of HC_3N and C_2H exist but are not due to high depletions, the ratio of the abundances of those two species will be significant for the inference of how $A_{\rm V}$ varied with $n_{\rm H}$ during collapse. In their work, Caselli et al. (1998) drew on published results for HC_3N in many cores; at the time of the submission of the present paper a comparably large set of data for C_2H do not exist in the literature.

4. Conclusions

The sharp decline in fractional ionization at $A_{\rm V} \simeq 2-3$ is here associated with the distinction between starless and star-containing cores in the RMC, through changes in turbulent support. This concept has led us to perform a preliminary study of the chemical evolution of a collapsing cloud, in which the cloud can first collapse only along the magnetic field lines. As the collapse proceeds, the fractional ionization declines until a multi-dimensional collapse modulated by ambipolar diffusion ensues. We show that while the details of the chemistry are broadly similar to other comparable studies that have much cruder models of collapse, the specific nature of the collapse - in particular, the density at which multidimensional collapse becomes significant - should be indicated by chemical abundances.

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