CHEMISTRY IN SHOCKED INTERSTELLAR GAS

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ABSTRACT. In its passage through the interstellar gas, a shock imposes massive and irreversible changes on the chemical composition of the gas. The synthesis of molecules from atoms and atomic ions can be highly efficient behind non-dissociative (i.e. slow) shocks. Results of kinetic calculations behind non-dissociative shocks are reviewed here, with emphasis given to the dependence of the postshock molecular composition on initial cloud properties. It is shown that a dense cloud shock can convert essentially all neutral atoms into various molecules. Even in diffuse and unshielded regions, a variety of molecules can attain a high abundance behind shocks. The suggestion that the widespread diffuse cloud species CH^+ is shock synthesized is critically examined in the light of new calculations.

1. INTRODUCTION

We know of many processes which can drive supersonic compressions (i.e. shocks) into ambient interstellar gas. Examples include supernovae remnants, HII region expansion, bipolar flows from young stars, stellar winds, cloud-cloud collisions, and galactic spiral density waves. Shocks reveal their presence in a number of ways: (1) Dynamical evidence for shocks includes observation of large atomic and molecular line widths (as in the core of the Orion molecular cloud), bipolar flows from young stars (e.g. Lada 1985), and velocity differences between molecules in a given line of sight which may indicate preshock and postshock gas (e.g. CH and CH^+ in diffuse clouds); (2) The hot postshock gas is seen by infrared emission from excited molecules, notably H_2, CO, and OH (e.g. Watson et al. 1980; Stacey et al. 1982; Beckwith et al. 1983; Watson et al. 1985). (3) Anomalous molecular abundances may, less directly, indicate the presence of shocks if these molecules are synthesized in the hot postshock gas. Molecules which have unusually high abundances in some regions, and for which shock synthesis has been suggested, include OH, H_2O, HCN, NH_3, SO, SO_2, CS, SiO, HCO^+, and CH^+.

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2. SHOCK STRUCTURE: HYDRODYNAMICS VERSUS MAGNETOHYDRODYNAMICS

A hydrodynamic shock consists of three regions: (a) a radiative precursor in which preshock gas may be dissociated, ionized, and heated by radiation from the hot, postshock gas; (b) the shock front, in which kinetic energy is dissipated as heat by atomic and molecular collisions; and (c) a cooling region in which the hot gas radiates until some final cold postshock state is reached. In recent calculations of molecular synthesis in non-dissociative hydrodynamic shocks, for which the shock speed (v_s) is less than $\approx$ 20 km s^{-1}, the effects of the radiative precursor have been ignored. The deposition of heat in the shock front occurs over a distance which is very small compared to the cooling region. Since the shock front is thin, the gas experiences an abrupt "jump" from upstream to downstream conditions.

Application of the conservation of mass, momentum, and energy across the shock front leads to the Rankine-Hugoniot relations, which allow the determination of postshock gas properties from preshock gas properties. For strong shocks (Mach number, M, much greater than one), the postshock density is independent of shock speed, ranging from a compression factor of ≈ 4 for atomic gas to ≈ 6 for molecular gas. The postshock temperature, on the other hand, increases with shock speed, as v_s^2. As the shocked gas cools, the requirement of pressure equilibrium produces continued compression. The density will increase until cooling ceases. Because faster shocks have higher postshock temperatures, the postshock gas will cool to higher densities. The compression factor is, in fact, proportional to M^2. Magnetic pressure will, however, limit the compression perpendicular to the field direction. A shock initially accelerates the gas to $\approx 3/4 v_s$. As the gas cools it continues to accelerate, approaching the shock speed (in the absence of a magnetic field). A line of sight through the cooling region of a shock is, therefore, sampling gas with a range of densities, temperatures, and speeds.

In the weakly ionized interstellar gas, the presence of magnetic fields can dramatically change the structure of a shock. The magnetic field is frozen to the ionized component of the gas, so that magnetic pressure can produce motion of the ionized gas through the neutral gas (ambipolar diffusion). The charged particles and magnetic field can move ahead of the neutral shock as a "magnetic precursor". Dissipation of energy by radiation in the precursor may be so great that the neutral shock becomes a continuous (C-type) shock, in which the density, temperature, and velocity of the gas vary smoothly through the shock. The notation C (for continuous) and J (for jump) was introduced by Draine (1980) to distinguish between the two classes of shock. An excellent review of megnetohydrodynamic shocks is given by McKee, Chernoff, and Hollenbach (1984). A shock will be C-type if: (1) the shock speed is low enough that magnetosonic waves can propagate ahead of the shock; (2) the fractional ionization is low enough to ensure weak ion-neutral coupling, thus permitting ions to stream through neutrals; and (3) the magnetic field if sufficiently strong. Two properties of C shocks are of great significance for the present topic of molecular synthesis. First, the postshock temperature in a C shock

is much lower than in a J shock of the same shock speed. Rates of high temperature reactions are, therefore, affected. Second the streaming velocity of ions with respect to neutrals, $v_n - v_i$, can be appreciable over a considerable distance. Ion-neutral reactions can be driven by this process, but their rates will be non-thermal. A computation of rates for such reactions requires knowledge of the cross sections in the relevant energy range.

A J shock will become a C shock if the magnetic field exceeds some critical value, B_{crit}, depending on shock speed, gas density, and fractional ionization. For low density ($n \approx 10$ cm^{-3}) gas with $n_e/n \approx 10^{-4}$, B_{crit} is several microgauss (μG) for shocks of speed near 10 km s^{-1}. For high density interstellar gas of lower fractional ionization, B_{crit} is several tens to several hundreds of μG.

3. MAGNETIC FIELD OBSERVATIONS

Troland and Heiles (1985) have recently reviewed the status of magnetic field measurements based on the Zeeman effect on HI and the Zeeman effect on OH. They find a typical "background" field strength of ≈ 5 μG for gas with densities in the range 0.1 to 100 cm^{-3}. There is no evidence of an increase in field strength over this range. For densities higher than about 100 cm^{-3}, measured field values show a weak increase, rising to ≈ 100 μG in some cases. These trends, a constant field up to $n \approx 100$ cm^{-3} and a slow increase to higher gas densities, are consistent with theoretical expectations. Initial compression is along field lines and does not increase B. At higher densities, when cloud motions are driven by self gravity, compression will also occur perpendicular to field lines and B will be amplified. During the latter process the field strength is predicted to increase as $B \approx n^k$, where k is 1/3 to 1/2.

Many exceptions and anomalies exist in the data, however: (1) Some 50 measurements of the HI Zeeman effect resulted in upper limits of 5 μG. Typical gas densities in these regions is 1-50 cm^{-3}; (2) No line of sight field greater than 0.8 μG exists in the Cas A Local Arm HI absorbing region, where densities may be as high as 100 cm^{-3}; (3) The Cas A Perseus Arm OH absorbing regions have field strengths of only 9 μG for each of the four velocity components. In these regions the density may be $\approx 10^4$ cm^{-3}.

A comparison of B_{crit} with measured field values suggests that C shocks will often occur. The data also suggest that many regions have $B < B_{crit}$ and would, therefore, experience J-type shocks. Furthermore, compressions moving along field lines will always produce J shocks. It seems reasonable to conclude that the interstellar gas is subject to both J and C shocks depending on local field strengths and flow directions.

If postshock temperatures reach values of $\approx 12{,}000$ K, all molecules will be rapidly dissociated. Molecular synthesis can begin again only after re-formation of H_2 (either on grains or via H^-). No calculations have been carried out of the formation of molecules after the passage

of a dissociative shock, although the relevant physical processes seem to be understood (Hollenbach and McKee 1979). The following sections review results for non-dissociative shocks ($v_s < 20$ km s^{-1}) passing through dense and diffuse interstellar clouds.

4. SHOCKED DENSE CLOUDS

The elevated temperatures in shocked gas can drive many chemical reactions which are ineffective at ambient cloud temperatures because of endothermicity or activation energy. Reactions between neutrals are particularly important because they are often slow in cold gas and because the neutral reactants can be abundant. As a result of the action of this hot chemistry, the passage of a shock will drastically change the composition of the gas.

The first calculation of postshock molecular processes to include a moderately elaborate system of chemical reactions was performed by Iglesias and Silk (1978). Hartquist, Oppenheimer, and Dalgarno (1980) considered the postshock chemistry of sulphur species. More recently, Mitchell (1984a,b) has reconsidered chemical processing in dense cloud shocks using a considerably more complete reaction system and exploring a range of shock speeds. Figures 1a and 1b (from Mitchell 1984a) show examples of postshock abundance profiles, in which fractional abundances (n(X)/n) are plotted as a function of time after the shock. In both figures, the shock speed is 10 km s^{-1} and the initial density is 10^4 cm^{-3}.

Postshock column densities are displayed as a function of shock speed in Figure 2. These results are from Mitchell (1984a) and illustrate a number of species which are expected to be dramatically affected by shocks. The column densities are normalized to a total (i.e. hydrogen) column density of 10^{21} cm^{-2}. In Figure 2a, the abundances of atomic H, C, N, and O are shown, as well as of H_2 and CO. For shock speeds greater than ≈ 5 km s^{-1}, the column densities of atoms decline as the available atoms are incorporated into various molecules. For shocks of speed $\gtrsim 15$ km s^{-1}, the atomic abundances increase again as molecules begin to be dissociated. The range of shock speeds for which interesting molecular synthesis can take place is, therefore, quite narrow. For shock speeds < 5 km s^{-1}, the postshock temperature is too low to drive exothermic reactions, while for shocks of speed $\gtrsim$ 17 km s^{-1}, the postshock temperatures are so high ($T \gtrsim 12{,}000$ K) that complete molecular dissociation takes place. For C-type (magnetic) shocks, considerably higher shock speeds, $v > 40$ km s^{-1}, are allowed before dissociation occurs.

From Figure 2b it can be seen that water is high in abundance for all non-dissociative shocks. It becomes, in fact, the most abundant oxygen-bearing molecule after CO. Water is formed by the endothermic hydrogen abstraction reactions $O(H_2H)OH$ and $OH(H_2H)H_2O$. OH is little enhanced in column density in dense cloud shocks, despite an initial increase in fractional abundance, because it is quickly converted into H_2O. Molecular oxygen is consumed in the shock for speeds up to ≈ 8 km s^{-1}, declines slightly in abundance for shocks with $8 \lesssim v \lesssim 13$ km s^{-1},

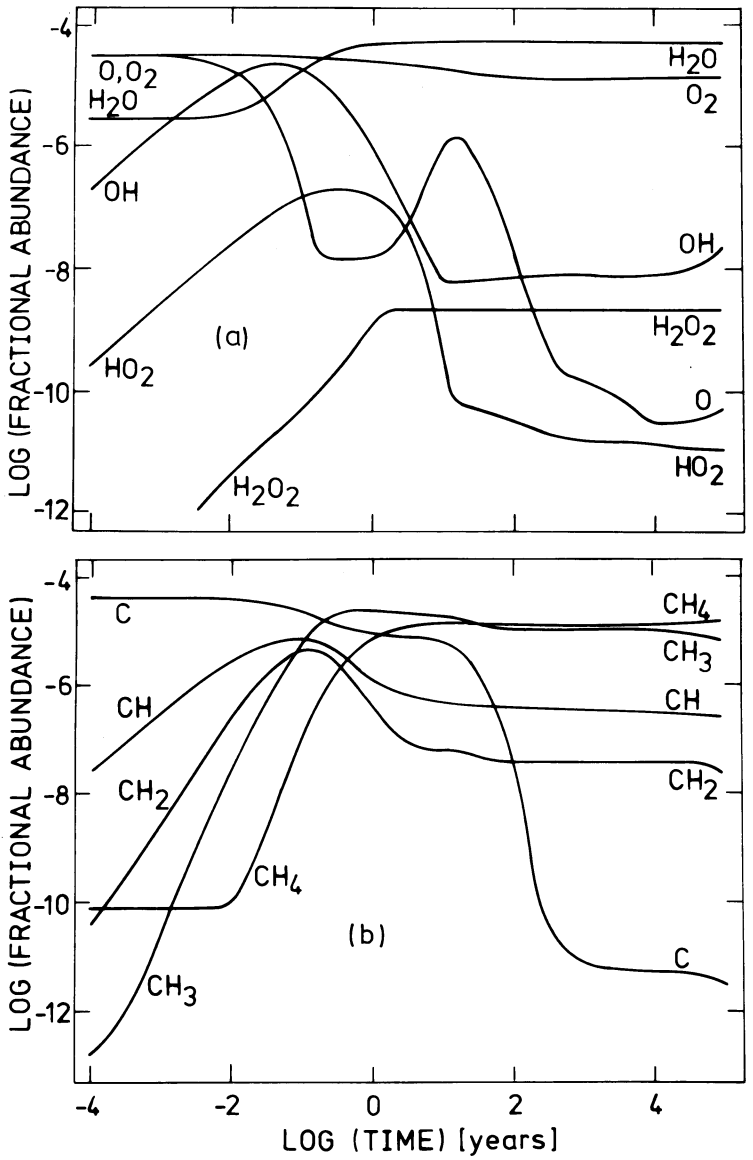

Figure 1: Postshock abundance profiles for selected species. Shock speed is 10 km s^{-1} and initial density is 10^4 cm^{-3}.

and is depleted by reaction with H_2 for faster shocks. The rather complex variation of O_2 with v is due to the temperature dependence of certain reactions as well as to the effect of the reaction $C(O_2,O)CO$.

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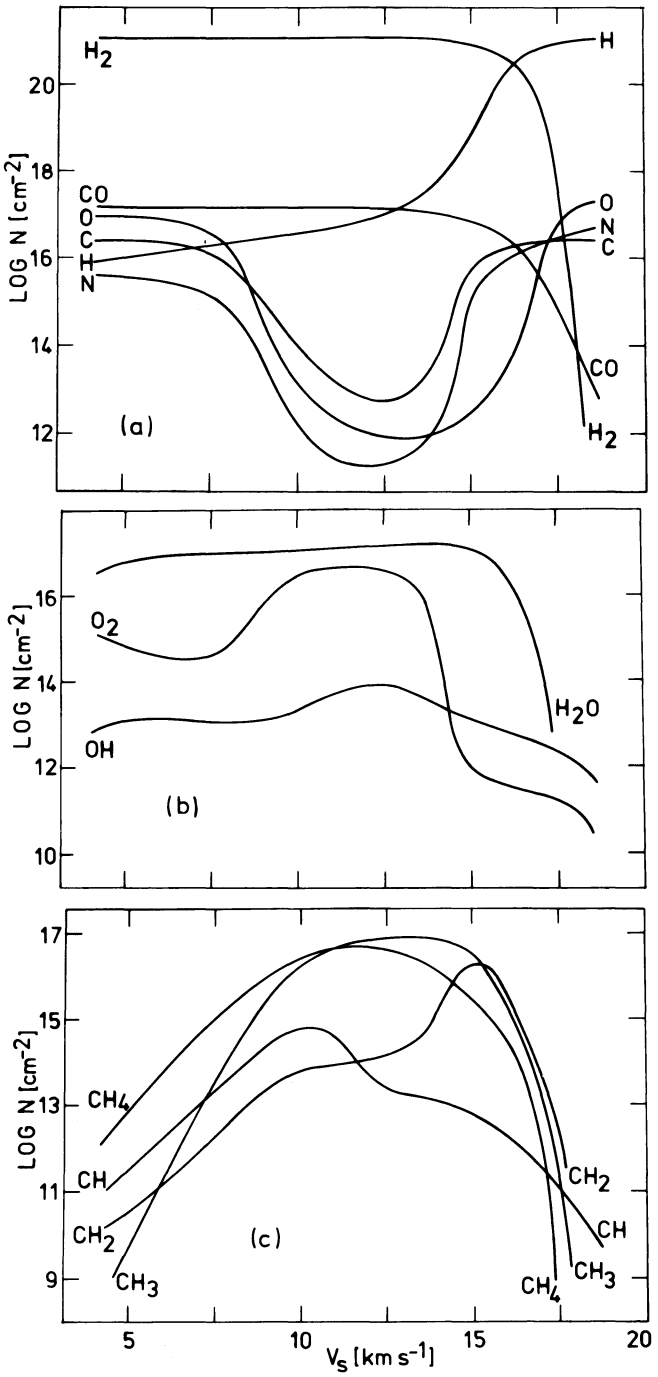

Figure 2: Postshock column densities as a function of shock speed. The initial gas density is 10^4 cm^{-3}.

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For shocks with $8 \lesssim v \lesssim 13$ km s^{-1}, atomic carbon is depleted quickly, so that the above reaction is ineffective and the O_2 abundance remains high.

Formaldehyde is abundant for the complete range of non-dissociative shock speeds. It is formed by the reactions

$$CH_3 + (O,O_2) \rightarrow H_2CO + (H,OH).$$

The production of formaldehyde requires CH_3, which is abundant because of the high initial atomic carbon abundance of these models ($C/n = 4 \times 10^{-5}$). H_2CO does not increase in abundance if the atomic carbon abundance is low (Iglesias and Silk 1978; Mitchell and Deveau 1982). The species HO_2 and H_2O_2 can attain quite high postshock abundances by reactions of O_2 with H_2.

All of the species CH, CH_2, CH_3, and CH_4 have high postshock column abundances for some or all of the range of shock speeds $5 < v < 17$ km s^{-1} (Fig. 2c). Synthesis is by successive reactions with H_2.

$$C \rightarrow CH \rightarrow CH_2 \rightarrow CH_3 \rightarrow CH_4.$$

Relative abundances among these species are also affected by destruction processes such as

$$CH_4 + H_2 \rightarrow CH_3 + H + H_2,$$
$$CH_4 + H \rightarrow CH_3 + H_2,$$
$$CH + H \rightarrow C + H_2.$$

Some species with two carbon atoms are predicted to be fairly abundant. For example, C_2H_4 and C_2H_5 both reach column abundances of $\approx 10^{15}$ cm^{-2}, due to the reactions

$$CH_3 + CH_3 \rightarrow C_2H_4 + H_2,$$
$$CH_3 + CH_3 \rightarrow C_2H_5 + H.$$

The nitrogen species CN, HCN, and NH_3 reach high postshock column abundances (up to $\approx 10^{17}$ cm^{-2}). CN and HCN form via

$$NH + C \rightarrow CN + O,$$
$$NO + C \rightarrow CN + O,$$
$$CN + H_2 \rightarrow HCN + H,$$

while ammonia is produced from N by successive reactions with H_2.

$$N \rightarrow NH \rightarrow NH_2 \rightarrow NH_3.$$

A number of sulphur species become abundant (Mitchell 1984b): HS and H_2S are formed from S by successive reactions with H_2; CS is formed via the reaction $CH + S \rightarrow CH + H$; and H_2CS is formed from CH_3 and S by $CH_3 + S \rightarrow H_2CS + H$. Because CH and CH_3 require atomic carbon for their

formation, the high abundance of CS and H_2CS is directly due to the initial high C abundance. SO is formed by the reactions

$$S + OH \rightarrow SO + H,$$
$$S + O_2 \rightarrow SO + O,$$
$$HS + O \rightarrow SO + H.$$

S_2 is somewhat enhanced in abundance due to the reaction $HS + S \rightarrow S_2 + H$, but does not become a major sulphur species because HS is quickly consumed in the formation of H_2S.

In summary, a major result of non-dissociative shocks in dense clouds is the conversion of neutral atoms into various molecules: O into H_2O and H_2CO; N into NH_3, CN, and HCN; C into CH_4, CH_3, CH_2, CH, and H_2CO; and S into H_2S and H_2CS, as well as smaller amounts of SO and CS.

The high postshock abundance attained by some of the molecules discussed above is due to the asumption of a high initial atomic carbon abundance. Philips and Huggins (1981) deduced a high abundance of CI from their observation of strong CI 609 μm emission from a number of sources. Tielens and Hollenbach (1985a,b) have constructed a model of the Orion region in which the CI 609 μm emission comes from a photodissociation region at the surface of the molecular cloud. Their model can explain well most of the atomic fine-structure emission lines from the Trapezium region, as well as the CO radio recombination lines. A necessary feature of the model to account for the intensity of the CI emission is a high incident radiation flux of $\approx 10^5$ times the interstellar average. Such a large radiation field is appropriate for the Orion region, but may be too high for other interstellar clouds from which CI emission is seen. In the Tielens and Hollenbach Orion model, a fairly high C abundance is maintained for a distance into the cloud corresponding to a hydrogen column density of $\approx 10^{22}$ cm^{-2}. Furthermore, for most of this distance, hydrogen is largely molecular, so that shock synthesis can proceed along the lines outlined above.

The calculations described above include reactions leading to the synthesis of hydrocarbon molecules, C_nH_m, with up to 6 carbon atoms. No hydrocarbon atoms with more than 3 carbon atoms achieved a high column density in these dense clouds. In contrast, Mitchell (1983; also see Mitchell and Deveau 1983) found that copious amounts of larger hydrocarbon molecules are formed behind a shock of speed 10 km s^{-1} passing into a cloud of lower density (100 cm^{-3}) but with a high initial C^+ abundance. The difference is due to the importance of the reaction $C^+ + H_2 \rightarrow CH^+ + H$ in low density clouds. When temperatures are high enough to drive this reaction, a sequence of rapid ion-molecule reactions is unleashed (e.g. see Figure 1 of Mitchell 1983) which lead to hydrocarbon ions $C_mH_n^+$. Recombination of such ions, together with neutral-neutral reactions, results in large abundances of neutral hydrocarbons. An interesting implication of these results is that a diffuse interstellar cloud with a high C^+ abundance and an appreciable fraction of hydrogen in molecular form may be converted by a shock into a dense interstellar cloud with high abundances of larger species. The postshock composition would differ from the steady-state

composition and would persist for long times. The clouds (or clumps) observed in the Perseus spiral arm towards Cas A may be an example of such a process. They may have recently been subjected to the galactic spiral shock (Roberts 1972). It has been suggested by Heiles and Stevens (1985) and Schwarz et al. (1985) that these clouds are not gravitationally bound and may be rebounding from a shock. Interesting velocity structure and unusual molecular abundances lend support to such an interpretation (Bell et al. 1986).

Many of the molecules in the Orion Molecular Cloud core emit over a wide velocity range. Some of the molecules in this "plateau" source are enhanced in abundance over normal molecular cloud abundances. Since the broad velocity molecules may be shock produced, the Orion plateau source is a useful region to test shock theories. Of the 10 species which are enhanced in the plateau source (Hjalmarson 1985), 7 are predicted to be enhanced by the shock models descibed above (namely H_2O, NH_3, CN, HCN, H_2S, SO, and CS). The molecules OCS and SO_2 are observed to be overabundant, in disagreement with the models of Mitchell (1984b). HCO^+ is enhanced in Orion, in disagreement with dense cloud shock models. If, however, some part of the preshock gas contains a high abundance of C^+, an enhancement of HCO^+ is expected (Mitchell and Deveau 1983). A quantitative comparison of these non-magnetic shock abundances with Orion plateau abundances is not appropriate, however, since an MHD shock is required to explain the infrared emissions from excited H_2, CO, and OH (Draine and Roberge 1982; Chernoff, Hollenbach, and McKee 1982).

5. SHOCKS IN DIFFUSE CLOUDS AND THE CH^+ PROBLEM

Elitzur and Watson (1978,1980) have suggested that the observed CH^+ in diffuse clouds may be produced in hot gas behind shocks by the reaction $C^+ + H_2 \rightarrow CH^+ + H$. They considered hydrodynamic shocks and incorporated a fairly limited chemistry which included CH^+, CH and OH. Their models, albeit with a limited reaction system, yield CH^+ column densities as high as 10^{13} cm^{-2}, consistent with observed amounts. Although the models appear able to reproduce the observed amounts of CH^+, some reservations remain: (1) It is surprising that quiescent diffuse cloud models are successful in explaining CH, CN, and C_2 in those sources with CH^+. (2) Since all CH sources are also CH^+ sources, we must accept the fact that virtually all diffuse clouds contain shocks, although, in most cases, there is no direct evidence for shocks. (3) Several diffuse clouds show a velocity difference of up to ≈ 3 km s^{-1} between CH and CH^+. If CH is in the cold postshock gas while CH^+ is in the hot postshock gas, such a difference is evidence for a shock with a line-of-sight velocity of ≈ 12 km s^{-1}. As shown by Roberge and Dalgarno (1982) and Lepp and Shull (1983), radiative stabilization of excited H_2 will occur in low density gas, permitting non-dissociative shocks of speed considerably higher than 12 km s^{-1}. For such faster shocks, one expects to find larger velocity differences between CH and CH^+ than have been observed.

Diffuse cloud shocks have recently been reconsidered by Mitchell and Watt (1985), using a much expanded chemical system. The purpose of this work was to reconsider the question of CH^+ shock synthesis and to identify possible additional species which might be abundantly formed in the hot postshock gas and might, therefore, serve as observational diagnostics for shocks. The calculations covered preshock gas densities of 5 to 50 cm^{-3}, shock speeds of 5 to 20 km s^{-1}, and several values of the molecular hydrogen fraction, $n(H_2)/n(H)$, from 0.001 to 1. Conclusions of this work are: (1) For a majority of CH^+ sources, the observed CH^+ column density exceeds the predicted postshock column density. For two sources, observed CH^+ abundances exceed model abundances by a factor of ten; (2) The high CN abundance observed in 14 sources is consistent with predicted abundances for cold postshock gas. Several sources, however, have a high CH abundance together with a low CN abundance, in conflict with the models; (3) The models predict that CO should be more abundant than CH by factors of 100 to 1000. For some sources, the CO column density exceeds that of CH by a factor of only 2 to 3; (4) Hot postshock CO, with a predicted column density of $> 10^{13}$ cm^{-2}, is a potential shock diagnostic; (5) Predicted abundances of H_2O, NH, and CH_2 are very close to observed upper limits; (6) A number of species not yet detected in diffuse clouds, including C_2H, NO, HCN, CH_2^+, CH_3^+, and HCO^+, attain column densities in excess of 10^{11} cm^{-2} in the hot postshock gas.

Table I lists postshock abundances of selected species for a model with speed 20 km s^{-1}, preshock gas density 10 cm^{-3}, and 5% of hydrogen (by number) in molecular form.

TABLE I
COLUMN DENSITIES IN THE HOT POSTSHOCK GAS (T>1000K)
(v_s = 20 km s^{-1}, n_0 = 10 cm^{-3}, and H_2/H = 0.05)

SPECIES	N(cm^{-2}) Postshock	Preshock	SPECIES	N(cm^{-2}) Postshock	Preshock
C	1.1(14)	4.8(11)	NO	1.5(11)	6.1(5)
CH	1.1(12)	7.5(7)	NH	5.1(11)	3.2(4)
CH_2	2.8(11)	9.3(7)	NH_2	1.3(10)	8.0(4)
CH_3	8.0(9)	5.6(5)	CN	2.7(11)	1.3(7)
C_2	2.6(11)	7.7(7)	HCN	3.7(11)	1.7(5)
C_2H	2.6(10)	3.7(7)	CH^+	2.6(12)	2.9(5)
C_2H_2	9.0(9)	4.0(3)	CH_2^+	3.8(11)	1.5(6)
C_3	1.3(10	7.5(2)	CH_3^+	5.2(10)	1.0(7)
CO	5.8(13)	9.3(9)	CO^+	4.1(10)	4.3(4)
CO_2	2.9(9)	1.6(3)	HCO^+	2.4(11)	6.7(7)
OH	3.3(13)	2.7(8)	OH^+	4.6(10)	8.5(4)
H_2O	8.7(11)	3.7(7)	H_2O^+	3.2(10)	8.0(4)

The tabulated column densities refer to hot postshock gas with T > 1000 K. Large amounts of CH, CO, and CN (underlined in Table I) can also be present in the cold postshock gas. For all other species in Table I,

the cold postshock gas makes at most a small contribution to the total observable column densities, because of rapid destruction processes, particularly photodissociation. The abundances in Table I are lower limits in the sense that an unattenuated mean interstellar radiation field was assumed. If some shielding were to be included, the abundances would stay high for a longer time, so that column densities would be higher. The ions CH_2^+, CH_3^+, and HCO^+ can reach high, perhaps observable column densities. Their abundances increase with the fractional abundance of H_2. For a model with shock speed of 20 km s^{-1}, initial density of 10 km^{-1}, and equal abundances of H_2 and H, the column densities of CH_2^+, CH_3^+, and HCO^+, are 1.5×10^{12} cm^{-2}, 3.0×10^{12} cm^{-2}, and 7.5×10^{11} cm^{-2}, respectively. CH_2^+ and CH_3^+ are formed from CH^+ by the fast hydrogen abstraction reactions $CH^+(H_2,H)CH_2^+$ and $CH_2^+(H_2,H)CH_3^+$. HCO^+ is formed from CH^+ and from OH (by way of the high temperature reaction $O(H_2,H)OH$).

Flower, Pineau des Forets, and Hartquist (1985), in a study of C-type (continuous) magnetohydrodynamic shocks in diffuse clouds, found that the change in fractional ionization produced by ion-molecule reactions, particularly $C^+(H_2,H)CH^+$, broadens the shock profile and reduces the neutral gas temperature. Pineau des Forets et al. (1986) have extended the MHD shock calculations, using a more complete diffuse cloud reaction network, to address the problem of CH^+ formation. They also present abundances of CH^+, CH, and OH for purely hydrodynamic shocks with initial density 20 cm^{-3}, $H_2/H = 0.1$, and shock speeds from 10 to 18 km s^{-1}. The hydrodynamic results of Pineault des Forets et al. are in good agreement with those of Mitchell and Watt (1985). The OH column densities agree to better than a factor of two, as do the CH^+ column densities for shock speeds less than 15 km s^{-1}. For faster shock speeds the CH^+ column densities of Pineau des Forets et al. (1986) are larger by factors of 2 to 3 than those of Mitchell and Watt. The difference appears attributable to the use of a different rate for the reaction $C^+(H_2,H)CH^+$. The rate used by Pineau des Forets et al., from Adams, Smith, and Millar (1984), becomes faster than the thermal rate used by Mitchell and Watt for higher temperatures (i.e. for faster shocks). Both calculations fail to produce the higher observed CH^+ column densities.

The MHD models of Pineau des Forets et al. (1986) produce more CH^+ than do purely hydrodynamic models and, in fact, succeed in producing the observed amounts of $\gtrsim 10^{13}$ cm^{-2}. An increase in CH^+ abundance occurs because the reaction $C^+(H_2,H)CH^+$ is driven by ion-neutral streaming, more than compensating for the lower temperature of C-shocks. The MHD models have difficulty, however, in reproducing the observed column densities of the excited rotational states of H_2, so that the applicability of the shock model for CH^+ formation remains in doubt.

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DISCUSSION

OMONT: NO is claimed to have been detected in the diffuse medium by Pwa and Pottasch using IUE towards ζ Oph.

IRVINE: SiO has been suggested as a chemical diagnostic of shocks, and this has been supported by the observation of broad SiO lines towards regions like Orion KL. The failure to detect SiO towards the supernova remnant IC443 has then been a puzzle. This has now been clarified by a recent detection of SiO towards IC443 by L. Ziurys and P. Friberg with the University of Massachusetts (FCRAO) 14 m telescope.

JURA: I just like to mention one other possible observational difficulty with the idea that CH^+ may be formed in shocks. For this to happen one requires fair amount of H_2 in pre-shocked region which essentially implies a fair amount of neutral sodium. If you look into the details of the kinematics, at least in some cases the neutral sodium is not present or is present not in abundance appropriate to pre-shocked cloud.

HARTQUIST: Draine and Katz have performed studies similar to those of Pineau des Forets, Flower, Hartquist, and Dalgarno. They obtained a lower ratio of $N(H_2, J=4)/N(CH^+)$ than we did, but also found that the model $N(H_2,J=4)$ in the shocks is at least comparable to the observed $N(H_2,J=4)$. The differences between their results and ours may arise from their adoption of higher photodissociation and photoionization rates, which lead to more rapid recycling through a chemical sequence which forms CH^+.

MELNICK: You showed atomic oxygen disappearing rapidly in the post-shocked gas in your C-type model. I don't think that the observations of OI in Orion support this picture. Werner and Ellis and their collaborators at Berkeley showed that the spatial distribution of OI 63 μm and H_2 emission are quite similar. Further, Crawford et al. (1986) have measured the OI 63 μm line profile and find it to be similar to that of $J = 16 \rightarrow 15$ CO, establishing OI 63 μm line emission as originating from the postshocked gas. The OI 63 μm emission from this region is bright, and I don't think that one can explain the observations if you rapidly destroy all the oxygen in the post-shocked region.

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