PANEL DISCUSSION: THE CO/H_2 ABUNDANCE RATIO

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ABSTRACT. The observational and theoretical information on the CO/H_2 abundance in a variety of astrophysical regions including diffuse clouds, dense star-forming regions, shocked gas and circumstellar envelopes is discussed and reviewed.

1. Introduction

The determination of the total amount of molecular hydrogen from measurements of CO millimeter emission lines in galactic and extragalactic objects is one of the more controversial topics in astronomy. Most of the debate has centered on the so-called CO/H_2 conversion factor, which relates the measured integrated CO J=1–0 antenna temperature to the total column density of H_2, and many reviews and papers have appeared on this topic (see e.g. Dickman et al. 1986; van Dishoeck & Black 1987; Israel 1988; Bloemen 1989; Elmegreen 1989; Maloney 1990; Solomon & Barrett 1991; Henkel et al. 1991; Combes 1991; Young & Scoville 1991). The discussion has largely been of an empirical nature, however, with little attention to the variation of the actual CO/H_2 *abundance* in the various astrophysical environments. The implicit assumption is often made that the CO/H_2 abundance is more or less constant and equal to the "canonical" value of 10^{-4}. However, it is known (e.g. from the *Copernicus* satellite data) that this assumption is not always true and that there are regions where hydrogen is mainly molecular but CO has a very minor proportion of the solar carbon abundance.

Since astrochemists are in a better position to explore the chemical questions rather than the empirical relations, we focussed the panel discussion on the actual CO/H_2 abundance, with discussion of the empirical CO/H_2 conversion factor only where relevant. The panel members were asked to make a brief statement about the current observational evidence for the CO/H_2 abundance in a variety of regions and to address questions such as: What are the theoretical expectations? What are the prospects for future observational tests of the models? If CO is not a good tracer of H_2 in some regions, which other species could be useful? This paper is an edited (rather than verbatim) version of the comments made by the panel members and of some of the questions raised by the audience.

2. Direct and indirect measurements

2.1. Direct measurements

Direct observations of both CO and H_2 are limited to only a few specific interstellar regions.

P. D. Singh (ed.), Astrochemistry of Cosmic Phenomena, 285–295.

TABLE 1. Direct measurements of CO/H_2 in interstellar clouds

Cloud	N(CO) (cm^{-2})	$N(H_2)$ (cm^{-2})	CO/H_2	CO/[C][a]	Method	Ref.
π Sco	1(12)	2(19)	5(-8)	4(-6)	UV abs	1
ζ Oph	2(15)	4(20)	5(-6)	4(-3)	UV abs	2
NGC 2024 IRS2	8(18)	<1(23)	>8(-5)	>0.10	IR abs	3
NGC 2264 IRS	5(18)	<1(23)	>5(-5)	>0.06	IR abs	4
Orion/KL shock	4(17)	3(21)	1.2(-4)	0.16	FIR em	5

[a] The reference abundance of carbon in all forms (gas and solid; atomic and molecular) has been taken to be the solar value of $[C]/[H]=4 \times 10^{-4}$ (Grevesse et al. 1991). About 60±20% of the carbon is thought to be in solid form.

References: 1. Jenkins et al. 1989; 2. Morton 1975; 3. Black & Willner 1984; 4. Black et al. 1990; 5. Watson et al. 1985.

In diffuse clouds, both molecules can be seen by their absorption lines at far-ultraviolet wavelengths superposed on the spectra of bright background stars. Since the lines are saturated, high spectral resolution and high S/N such as provided by the *Copernicus* satellite are necessary to derive reliable column densities. The smallest CO column density detected with *Copernicus* is about 10^{12} cm^{-2} toward the star π Scorpii, whereas the largest column of about 2×10^{15} cm^{-2} was found toward ζ Ophiuchi. The observational data for these two stars are summarized in Table 1, which is an updated version of the table presented by van Dishoeck & Black (1987). The measured CO abundance, $N(CO)/N(H_2)$, varies by nearly two orders of magnitude for the various diffuse clouds. In terms of the total available carbon in the cloud, however, only a small fraction appears to be in the form of the CO. Even in the ζ Oph cloud, CO/[C] $\lesssim 0.01$. In the near future, high resolution ultraviolet observations of CO in thicker translucent clouds ($A_V >1$ mag) should be possible with the Goddard *High Resolution Spectrometer* on board the *Hubble Space Telescope* (HST). At the time of writing it was not yet clear, however, whether any direct observations of H_2 in such clouds would also be possible with HST.

Direct observations of CO and H_2 can also be made in thick molecular clouds through absorption lines at near-infrared wavelengths against embedded infrared sources. Measurements of CO lines in the v=1←0 and 2←0 vibrational bands at 4.6 and 2.3 μm have been reported for a number of sources, but only for the cases of NGC 2024 IRS2 and NGC 2264 IRS have simultaneous limits been obtained on lines of H_2 in the v=1←0 band at 2.1–2.2 μm. The results are summarized in Table 1 and indicate CO/H_2 abundances consistent with the canonical value of $CO/H_2 \approx 10^{-4}$ usually assumed for dense clouds. With improved cryogenic echelle infrared spectrometers, the actual detection of these H_2 absorption lines seems possible in the near future. Extension of this method to a larger number of clouds will also be very important, since the regions probed so far are warm star-forming clouds, where molecules may have been released from the grains (see also §5).

Finally, both CO and H_2 can be observed by their high-J rotational and vibrational transitions in emission in very warm, disturbed gas such as the Orion/KL shocked region. The derived CO/H_2 abundance is 1.2×10^{-4}, consistent with the limits found above. This last determination is less "clean", however, since the high-J CO lines refer to gas with $T \approx$750 K, whereas the H_2 v=1→0 lines arise in gas with $T \approx$2000 K, so that it is not obvious whether the same volume of gas is sampled. Observations of the pure rotational lines of H_2 may provide a better comparison. In dense clouds, gaseous CO accounts for a substantial fraction of the total available carbon, $CO/[C] \gtrsim 0.1$.

2.2. Indirect measurements

In most cold interstellar clouds, H_2 is not directly observable so that tracer molecules like CO need to be used to determine molecular masses. Although the millimeter lines of CO are easily detectable, they are difficult to interpret in terms of column density because the lines are almost always optically thick. Various methods have been put forward to determine empirically a relation between the integrated ^{12}CO 1→0 line intensity I_{CO} and the H_2 column density $N(H_2)$. For completeness, we summarize them here briefly (see above references for more details and possible pitfalls):

- I_{CO} vs A_V: determine A_V from star counts; convert A_V to $N(H_2)$ using the gas to extinction ratio derived for diffuse clouds, assuming that this same relation also holds for denser clouds. Since the clouds may contain a non-negligible fraction of atomic hydrogen, an independent measurement of N(H) is needed.
- $N(^{13}CO)$ vs A_V: determine ^{13}CO column densities from observations of optically thin lines assuming LTE. Determine $N(H_2)$ from A_V as above. $N(^{12}CO)$ can be found by adopting a $^{12}CO/^{13}CO$ abundance ratio. This conversion factor has been calibrated for clouds in which most gas-phase carbon is in CO.
- *Virial theorem:* assume that the cloud is in virial equilibrium, and use the observed line width and size to determine its mass. This leads not only to the proportionality factor, but also to the important result that $X = N(H_2)/I_{CO} \propto n_H^{1/2}/T_{ex}$, where T_{ex} is the excitation temperature of CO. A major problem in applying the virial theorem is the complicated morphology and small-scale structure of most clouds.
- *Gamma ray method:* compare the galactic distribution of diffuse gamma radiation, resulting from interactions of cosmic rays with hydrogen nuclei, with maps of H I and ^{12}CO J=1→0 emission to derive X. This method is biased toward GMCs in the inner Galaxy.
- *IRAS 100 μm:* compare the distribution of IRAS 100 μm emission, originating from dust grains in the clouds, with maps of H I and CO J=1→0 emission to determine X. This method assumes not only that the dust emissivity properties are known with sufficient accuracy, but also that they are similar in diffuse atomic and molecular gas.

A common characteristic of these methods (except the second one) is that the CO/H_2 abundance does not enter explicitly in the analysis, and that they refer to global scales of order one square degree or larger. Nevertheless, it is remarkable that these completely different and independent methods yield a similar conversion factor, $X = N(H_2)/I_{CO} \approx 2.5 \times 10^{20}$ cm^{-2} K^{-1} km^{-1} s within a factor of two. The largest deviations from this value are found for the Galactic Center (Blitz et al. 1985) and for some (but not all!) high-latitude clouds (de Vries et al. 1987), where X appears an order of magnitude smaller. For clouds in the outer Galaxy (Digel et al. 1990) and in the Magellanic Clouds (Cohen et al. 1988), the conversion factor may be significantly larger (see §4).

3. Diffuse and translucent clouds and PDRs

Table 1 illustrates the fact that carbon is still mostly in atomic form (as C^+) in diffuse clouds with $A_V \lesssim 1$ mag. For the thicker translucent clouds with $A_V \approx$1–5 mag, carbon is gradually transformed into CO, and the CO abundance increases by two orders of magnitude in this regime (van Dishoeck & Black 1988). As Figure 1 of van Dishoeck (this volume) shows, the exact location of the transition depends on the physical parameters of the cloud, such as temperature, density, column density and incident radiation field. Any conversion factor which assumes that the CO/H_2 abundance is constant at about 10^{-4} is therefore likely to fail for translucent clouds. This applies in particular to the ^{13}CO method, which has been demonstrated to lead to an underestimate of $N(H_2)$ by an order of magnitude in some cases (Gredel et al. 1991). Observational tests of this transition zone should be possible through absorption line studies with the *HST*.

Since the CO abundance varies so drastically for translucent clouds, it may be better to turn to other molecules whose abundances are nearly constant. A good candidate is CH, for which the column densities have been shown to scale linearly with those of H_2 up to A_V of a few (Danks et al. 1984; Mattila 1986).

A similar transition of carbon from atomic to molecular form occurs for denser, warmer photon–dominated regions (PDRs) (Tielens & Hollenbach 1985). The main difference with the translucent clouds is that the transition occurs deeper into the cloud, especially if the gas has a "clumpy" structure. Since such PDRs are ubiquitous and may contribute significantly to the total emission from galaxies, it is important to calibrate the CO/H_2 ratio for these regions separately. Unfortunately, such a measurement will prove extremely difficult, because of the varying abundances with depth into the PDR. In particular, hydrogen will become molecular around $A_V \approx 2$ mag, but the C^+–C–CO transition does not occur until $A_V \approx 4$ mag. These spatially distinct zones within the PDR will have vastly different temperatures ($\approx$500 K versus 50 K) and this will complicate the derivation of the CO/H_2 ratio considerably. Probably the ideal source to examine is a nearby cloud–edge with a strong source of external UV radiation, where these zones within the PDR can be spatially resolved. Besides this, at least two other limitations confront the observations:

(1) *Direct observations of warm H_2.* The large energy–level spacing and lack of permanent dipole moment make H_2 simultaneously difficult to excite and difficult to observe. Observations of the ground–state pure rotational quadrupole lines provide the best method for determining the H_2 content of the PDR's. At current instrumental sensitivities, H_2 column densities of $< 10^{21}$ cm^{-2} can be detected in the (0–0) $3\rightarrow1$ and $4\rightarrow2$ transitions at 17 and 12 μm, respectively, if the gas temperature is $\geq$300 K (Parmar et al. 1991). With SIRTF, similar column densities will be detectable in gas at temperatures as low as 100 K.

(2) *Unambiguous detection of CO emission from the PDR.* In order to select CO emission from the hot PDR region where the H_2 emission arises and to discriminate against emission from cooler material deeper inside the PDR, one must observe an appropriately high CO transition. If we assume that the warm PDR region is reasonably dense and has a total column density of 10^{21} cm^{-2}, the J=9$\rightarrow$8 transition at about 1 THz can be detected with current instrumentation as long as the CO abundance is $>10^{-6}$. Unfortunately, the predicted CO abundance in this warm region is at least an order of magnitude lower than this limit (Burton et al. 1990).

4. Global CO emission

How important are the regions in which CO makes up only a small proportion of the solar carbon abundance globally and what would be their effect on the overall conversion factor? Conversely, how can the conversion factor be nearly constant, when the CO abundance is varying considerably? Several explanations have been advanced to explain (and mostly comfort) the existence of the empirical proportionality factor. The first assumes that clouds are statistically identical and small enough not to shadow each other along the line of sight. In this case, the CO luminosity merely counts the number of clouds intercepted by the beam, and is proportional to the molecular mass. A more sophisticated explanation is

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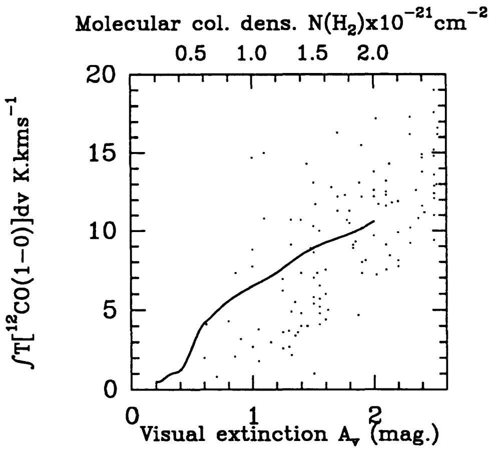

Figure 1. solid line: *The ^{12}CO (1–0) integrated intensity across a spherical cloud is plotted as a function of the H_2 column density along the line of sight (according to a Monte Carlo calculation by Guélin & Cernicharo 1988). The cloud, inspired by the dark cloud Heiles Cloud 2 in Taurus, has density/temperature ranging from 100 cm^{-3}/20 K at the periphery to 1000 cm^{-3}/10 K at the center and a radius of 1.5 pc. The CO fractional abundance is taken from calculations by van Dishoeck & Black (1988) for an attenuated IS radiation field; it varies from 5 10^{-6} to 4 10^{-4}.* **dots:** *the intensities actually observed around Heiles Cloud 2 (from Guélin & Cernicharo 1987).*

the one advanced by Dickman et al. (1986), which assumes that the clouds (mostly dense GMCs) are in virial equilibrium and that CO is thermalized (see §2.2). A third explanation proposes that the molecular gas is dominated by relatively low density "halos" of the kind discussed above, where CO is subthermally excited (Guélin & Cernicharo 1987). Monte Carlo radiative transfer calculations for "realistic" halo + small core models, inspired by the clouds in the Taurus region, show that the CO intensity increases almost linearly with $N(H_2)$ along most lines of sight (see Figure 1); the derived proportionality factor is close to the observed one (Guélin & Cernicharo 1988). Basically, the bulk of the gas lies in regions with $n(H_2)$=100–300 cm^{-2}, half-way between the regime of thermalization where T_{ex}=constant, and the "low excitation" regime, where the Einstein coefficient divided by the optical depth is much larger than the collisional rate ($A/\tau >> C$) so that the optically thick line intensities are still proportional to the molecular column density.

Observations show that at large scales, the molecular mass lies mostly in cloud halos which are presumably far from virial equilibrium, thus supporting the last model (see Guélin & Garcia-Burillo 1991): the ^{12}CO and ^{13}CO J=2–1 and 1–0 line intensities observed in the Taurus region as well as in nearby galaxies, such as M 51 and NGC 891, imply the existence of a massive low density component (in the Taurus region, this component is directly observed through star counts, as e.g. for the cloud of Fig. 1). Recently, Wright et al. (1991) (see Wright, this conference) have reported intensities of the ^{12}CO J=1–0 through 5–4 lines averaged over the whole Galaxy, as observed by *COBE*. These intensities, despite their low signal–to–noise ratio and the lack of ^{13}CO data, also imply the presence of two molecular components, the most massive of which has T_{ex} ≈5 K and is thus either extremely cold, or, in better agreement with the higher resolution studies, subthermally excited.

The halo model has important consequences for the constancy of the CO to H_2 conversion factor. Since halos are likely to be photon–dominated or "translucent" regions of the type discussed in §3, the relative abundances of H_2, ^{12}CO and ^{13}CO may vary considerably. In the model of Guélin & Garcia–Burillo, the $I(CO)$ will vary accordingly. Even if $N(H_2)/I(CO)$ could stay constant when averaged over large regions with similar global properties or entire galaxies, one may expect large changes when comparing intrinsically different regions such as arm and interarm regions or regions hosting active nuclei. A related question that needs further exploration is the extent to which the different regions show different conversion factors when CO J=2–1, 3–2, ... are considered rather than the 1–0 line (see also §3).

The CO/H_2 abundance and the conversion factor are also not well–determined in the outer Galaxy, where the average density of the clouds is probably lower (Digel et al. 1990). Moreover, the presence of a $[^{12}C]/[^{13}C]$ gradient across the Galaxy may affect some of the results (Langer & Penzias 1990). In regions of lower metallicity such as the Magellanic Clouds, significantly higher conversion factors have been claimed (e.g. Cohen et al. 1988; Maloney & Black 1988; Israel & de Graauw 1991; Johansson 1991), although for the dwarf irregular galaxy IC 10 X appears close to "normal" (Wilson & Reid 1991). Because the transition of carbon from atomic to molecular form depends on the CO self–shielding, it will occur deeper into the cloud in metal–poor regions, because it takes longer to build up the necessary column density. Thus, metal–poor clouds have relatively less CO compared with clouds in our own Galaxy, *provided* they are not larger than the average clouds in our Galaxy. How do we measure the amount of H_2 in these cases, where all other molecules also have low abundances? One possibility would be to use the fine–structure emission of C II as a measure, since most of the carbon is probably in that form. Indeed, a large–scale correlation between C II and CO emission has already been established both observationally and theoretically for warm PDR gas, including that in luminous galactic nuclei (Stacey et al. 1991). The problem is that not only the "H_2" clouds, but also the H II regions and H I clouds are sampled in this way, and it is not clear how to distinguish the molecular part from the rest of the interstellar "mess", especially in regions of low C II surface brightness (see also Madden et al. this volume; Wright et al. 1991). Another possibility would be to use the dust IR emission, but this suffers from the same problem. Optical and UV absorption lines might be a third possibility, if strong enough background stars can be found.

5. Solid CO

The direct measurements of the CO abundance in dense clouds indicate that at least 10% of the carbon is in the form of gas–phase CO. The best estimate of the amount of carbon in solid form (such as graphite, PAH's, organic refractory) is 60±20% (van Dishoeck et al. 1991). These numbers do not exclude the possibility that the gas–phase CO abundance may vary by factors of 2–3 from cloud to cloud, depending on the nature of the dust (Greenberg 1991). How much of this CO can be depleted onto grains in the densest regions? It is well known that the time–scales for gas–phase molecules to collide with grains and stick on them is very short in dense clouds with $n_H \gtrsim 10^5$ cm^{-3}. What happens to the CO when it is depleted onto grains? Will it just sit there and eventually be released back into the gas phase, or will it be transformed into other molecules? How could this affect the gas–phase CO/H_2 abundance?

Evidence for molecules adsorbed on the surfaces of grains comes from infrared observations toward protostellar sources, which show in addition to the sharp gas–phase CO lines a prominent broad absorption feature near 2140 cm^{-1} (4.6 μm) generally attributed to solid CO (Lacy et al. 1984; Geballe 1986; Whittet et al. 1988, 1991). Analysis of the relative strengths of the features shows that the solid CO abundance varies from about 10^{-5} to less than about 10^{-7} with respect to total hydrogen. In all cases, this is significantly less than the canonical value for the gas–phase CO abundance of 10^{-4}. However, the shape of the feature may provide important information on the history and evolution of the CO.

Figure 2 shows that the solid CO band consists of a narrow ($\sim$ 5 cm^{-1}) feature centered at about 2140 cm^{-1} and a broader ($\sim$ 10 cm^{-1}) wing at about 2136 cm^{-1} (Tielens et al. 1991). Both the peak position and width of the narrower and generally stronger component vary from source to source. Laboratory studies suggest that the narrow CO band occurs in mixtures dominated by non–polar molecules (i.e., CO itself, CO_2, O_2, N_2, CH_4), while the broader component is due to polar mixtures such as H_2O (Sandford et al. 1989). Figure 2 compares the observed spectra at moderate resolution ($\lambda/\Delta\lambda$ =1200) towards NGC 7538 IRS 9 and AFGL 2136 with laboratory spectra of solid CO and a mixture of CO/H_2O=1/20. Note that AFGL 2136 is the only known spectrum in which the narrow 2140 cm^{-1} component is absent. Its broad feature at 2136 cm^{-1} is well fit by the H_2O–rich mixture. The spectrum of NGC 7538 IRS 9, on the other hand, is dominated by a narrow component, which is well fit by pure solid CO. In most other sources, the data are better fit by mixtures dominated by N_2 or CO_2, whereas in a few cases O_2 dominated mixtures provide the best agreement.

These results unambiguously demonstrate that there are (at least) two independent grain mantle components along many lines of sight. One component is dominated by a non–polar mixture and carries the narrow solid CO feature. The other is H_2O–rich and is probably the carrier of the broader solid CO component, as well as the 3.08 and 6.0 μm H_2O–ice bands. The solid CO/H_2O ratio is always much less than one ($\lesssim 0.1$). This dichotomy in grain mantle compositions may reflect chemical and/or physical variations during the accretion process. In view of the low abundance of CO in grain mantles and its high abundance in the gas phase, it is likely that most of the accreted CO has reacted with atomic H or O to form molecules such as H_2CO, CH_3OH, and CO_2 (Tielens & Allamandola 1987). In this model, the H–rich conditions required to form H_2O-rich ices also transform CO into CH_3OH. Non–polar grain mantles would then reflect accretion conditions with little atomic H available (i.e., high density; Tielens & Hagen 1982).

Alternatively, models based upon the difference in volatility between CO and H_2O can be developed. In such models, accretion takes place in a dark molecular cloud. A newly formed star in such an environment will heat up the surrounding dust, leading to partial evaporation. Close to the star only the cores remain. Farther out, where the temperature drops below 100 K, strongly H–bonding molecules (e.g., H_2O, CH_3OH, NH_3) can survive in a grain mantle, but more volatile molecules (i.e., CO) will evaporate. When the temperature drops below 50 K, a molecule such as CO_2 will also remain frozen out. Finally, at large distances from the star (i.e., in the dark cloud) the temperature is less than 15 K and highly volatile molecules such as CO (and O_2, N_2, CH_4) remain in the grain mantle. Thus, the birth of a new star will lead to a temperature stratification which in turn will lead to grain mantle separation.

Each of these classes of models has pros and cons. Heating of grain mantles followed by outgassing has undoubtedly played a role around luminous sources such as the Orion BN/KL region. Both the shape of the 3.08 μm ice band (Smith et al. 1989) and the observed gas phase abundances in the hot core and compact ridge (Walmsley 1989) attest to that. However, this model would predict that grain mantles in dark clouds far from embedded objects would be dominated by non–polar molecules such as CO. Yet, background stars behind the Taurus dark cloud show also separate H_2O–rich and non–polar grain mantle components (Tielens et al. 1991). In this case heating has played no role. It is likely that both types of mechanisms are of importance in interstellar clouds. Chemistry may dominate the observed variations in dark clouds, while volatility is important around (some) protostars. Further observations of solid CO as well as other grain mantle constituents will be very important to settle these issues.

In summary, the observations clearly demonstrate that CO does freeze out onto grains

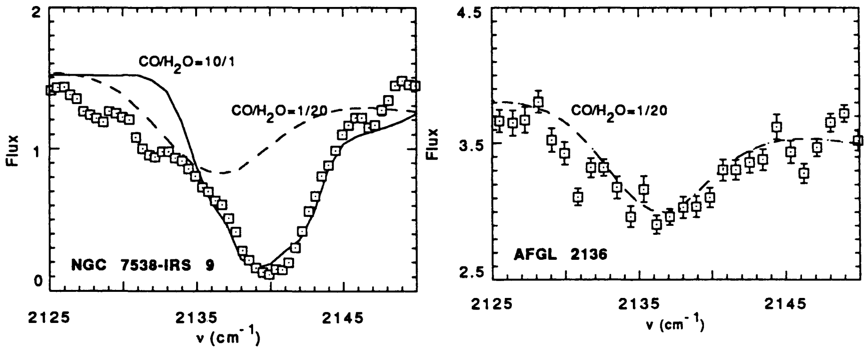

Figure 2. *The solid CO band toward the infrared source NGC 7538–IRS 9 is well fit in peak position and width by a mixture dominated by CO (solid line). Mixtures dominated by H_2O (dashed line) peak at lower frequencies and are broader than observed. In contrast, the spectrum of AFGL 2136 reveals only the broad component associated with H_2O–rich grain mantles (dashed line). See Tielens et al. (1991) for details. The error bars are smaller than the symbol, except where shown. Note also the weak gaseous CO feature.*

in dense interstellar clouds, but with different chemical results depending on the physical surroundings. The total amount of carbon depletion is not well known, however, especially in the coldest and densest protostellar condensations where the densities may be as high as $10^8 - 10^{10}$ cm^{-3} and where CO depletion could be significant. Comparison of submillimeter continuum observations with $C^{18}O$ maps of regions such as NGC 2024 (Mezger et al. 1988) and NGC 1333 (Sandell et al. 1991) may provide further insight into this question.

6. Dissociative shocks and protostellar outflows

Shock waves propagating through the interstellar medium at speeds faster than about 50 km s^{-1} are dissociative; they result in the temporary destruction of any molecules which enter them. The CO/H_2 abundance ratio behind dissociative shocks is presently not constrained by observation, primarily because such shocks are usually accompanied by slower, non–dissociative shocks which are far more luminous sources of molecular line emission and which therefore mask much of the molecular line spectrum which would be specific to fast shocks. The *theoretical* predictions for CO/H_2 in the dissociative case are outlined below. For non–dissociative shocks, the CO/H_2 abundance presumably does not deviate much from the “canonical” value of 10^{-4}, as found for Orion/KL (see Table 1).

Upon passing through a fast shock front, interstellar gas is rapidly heated to temperatures greater than $\sim 10^5$ K, resulting in the complete and rapid dissociation of molecules and the partial ionization of atoms via collisional processes (Hollenbach & McKee 1980). All information about the chemical state of the preshock gas is therefore lost. The shocked gas eventually cools, primarily via emission in optical and ultraviolet lines of atoms and atomic ions, and starts to recombine. Once the temperature falls below a few thousand degrees, molecule reformation ensues, starting with H_2 formation, which occurs in the gas phase via the H^- intermediary and – if sufficiently cool grains survive – in reactions catalysed on grain surfaces. A further reaction of H_2 with atomic oxygen leads rapidly to OH formation, and reactions of OH with C or C^+ result in the production of CO. Detailed modeling has shown (Hollenbach & McKee 1989; Neufeld & Dalgarno 1989) that provided grain catalysis of H_2 formation is moderately efficient, hydrogen is almost entirely incorporated into H_2 and carbon into CO by the time that the shocked gas has cooled to a temperature of a few hundred degrees. The time required is $\sim 10^7 \mathrm{yr}/n_0$, where $n_0 \, \mathrm{cm}^{-3}$ is the particle density in the preshock medium. The CO/H_2 abundance ratio will therefore simply reflect the gas–phase elemental abundance of carbon, which may have been somewhat modified as the result of carbonaceous grain destruction in the region behind the shock front.

If grain catalysis is ineffective – either because grains are absent or because they have been heated within the shocked gas to temperatures at which any adsorbed atoms evaporate before they have the chance to react – molecule reformation behind the shock is incomplete. Detailed studies have revealed (Neufeld & Dalgarno 1989) that in this circumstance the final H_2 abundance is only $\sim 10^{-3}$, while the fraction of gas–phase carbon in CO may be as large as ~ 0.1. In the absence of grain–catalysed H_2 formation, therefore, dissociative shocks may leave the interstellar medium in a rather exotic chemical state, in which the gas is largely atomic but possesses a substantial CO abundance, with a CO/H_2 abundance ratio of $\sim 100 \, [\mathrm{C}]_{\mathrm{gas}}/[\mathrm{H}]$.

The theoretical results for fast shocks are similar to those obtained for molecule formation in the ejecta of supernovae such as SN 1987A (Lepp et al. 1990) and in grain–free protostellar outflows (Glassgold et al. 1991). In the latter case, the deficiency of H_2 can be traced to the short time–scales in these winds. The CO/H_2 ratio is therefore sensitive to the mass–loss rate: most of the carbon will be transformed into CO for $\dot{M} \geq 3 \times 10^{-6} \, M_\odot \, \mathrm{yr}^{-1}$, whereas most of the hydrogen will be molecular only for $\dot{M} \geq 10^{-4} \, M_\odot \, \mathrm{yr}^{-1}$. Moreover, the CO quickly gets so cold that its millimeter transitions are unobservable until the wind interacts with the surrounding molecular cloud far from the protostar. Care should therefore be taken in inferring H_2 column densities and envelope mass–loss rates from radio observations of extremely high velocity (EHV) H I and CO flows near protostellar objects.

7. Circumstellar envelopes

The CO/H_2 ratio in the deep interior of circumstellar envelopes of evolved stars is largely determined by the temperature of the star (Glassgold & Huggins 1982). For $T_\star >$2500–3000 K, the hydrogen will be atomic; otherwise it is expected to be molecular. Carbon will be mostly in the form of CO for almost all evolved stars, simply because of the large binding energy of this molecule. Of course, if the star has an H II region, such as is found in the chromosphere of α Ori and in proto–planetary nebulae, the high temperatures and levels of dissociating radiation will alter this situation – and differently for CO and H_2. Thus, the CO/H_2 abundance ratio in the inner circumstellar regions of evolved stars may vary considerably from star to star.

In the outer part, the relative amounts of H and H_2 and of C^+ and CO, and the location of the transition zones, are determined by the effective line–shielding in the photodissociation of H_2 and CO (Glassgold & Huggins 1982; Mamon et al. 1988). Other effects such as ion–molecule reactions, fractionation processes and grain chemistry may also play a role in the outer part. If $T_\star < 3000$ K and if there are no internal sources of UV radiation, the CO distribution will be less extended than the H_2 distribution, simply because of the larger abundance of hydrogen. Without the above–mentioned restrictions on the nature of the star, other situations become possible.

Although CO emission from circumstellar envelopes is readily observed, measurements of H I and/or H_2 are very rare. For α Ori ($T_\star \approx 3500$ K), 21 cm radiation from the H I envelope has been detected (Bowers & Knapp 1987), and one can infer from other observations that carbon is more fully associated into molecules than is hydrogen, i.e.,

$CO/H_2 \gg 2$ $[C]_{gas}/[H]$. For the best studied and chemically important AGB star, IRC +10216 ($T_\star \approx 2300$ K), interesting upper limits on the 21 cm emission have been obtained by Zuckerman et al. (1980) and by Knapp & Bowers (1983). These limits correspond to a mass of $\approx 10^{31}$ gr, close to the amount injected into the envelope from the upper atmosphere of the star (Glassgold & Huggins 1982). Keady & Ridgway (1991) have recently searched for the H_2 ro–vibrational lines at 2 μm and find that $\dot{M}(H_2) < 4 \times 10^{-5}$ $M_\odot$ yr^{-1}. Because the CO abundance and the mass–loss rate can both be determined from a detailed analysis of the spatial variation of the CO millimeter line emission – $CO/H_2 = 6 \times 10^{-4}$ and $\dot{M} = 3 \times 10^{-5}$ $M_\odot$ yr^{-1} –, an upper limit to the H I/H_2 ratio for IRC +10216 is H I/$H_2 < 5 \times 10^{-3}$ (Huggins et al. 1988). For almost all other red giant winds, observers generally determine the mass–loss rate by assuming that all carbon is in CO and hydrogen in H_2, i.e. $CO/H_2 = 8 \times 10^{-4}$ for C stars and 3×10^{-4} for Miras (Knapp & Morris 1986).

8. Concluding remark

Although observations indicate a remarkable constancy in the conversion factor of integrated CO line intensity to H_2 column density on a global scale, various theoretical arguments and observational data suggest that the actual CO/H_2 abundance may vary substantially locally in certain astrophysical environments. Indeed, there are regions where CO/H_2 is significantly lower than the canonical value of 10^{-4}, such as diffuse clouds, PDRs, and possibly very dense protostellar condensations. On the other hand, several examples have been given where CO/H_2 may be substantially higher than 10^{-4}, including grain–free dissociative shocks, supernova ejecta, protostellar winds and some circumstellar envelopes. Care is required with the traditional analysis in these cases.

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