

Molecular clouds : Cosmic distilleries

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Abstract. Since the first detection of a molecular microwave transition (OH) in 1963, the study of interstellar molecules has made important contributions to a wide range of astronomical problems. In addition, an entirely new area of research, interstellar chemistry, has been established. Interstellar molecules are the primary probes of the *cold, gaseous* component of the interstellar medium in the Milky Way and other galaxies.

Three areas of currently active research have been arbitrarily selected for review in this article : molecular cloud chemistry; isotopic abundances; and the distribution of molecular clouds in other galaxies. Because all three areas are rapidly changing due both to new observations and theoretical work an attempt has been made to give the current status of each area of research and to emphasize the general ideas which are not likely to become obsolete unless our present ideas are fundamentally wrong.

Regrettably, other equally important and active areas of research such as star formation, bipolar flow regions, OH/IR stars, interstellar masers, and others are not discussed in order to maintain a reasonable length.

Key words : interstellar molecules—interstellar chemistry—isotopic abundances—galaxies: molecular distributions

1. Introduction

Interstellar molecules provide a unique tool for the study of the physical conditions in molecular clouds, regions of star formation, isotopic abundances, interstellar chemistry, the interaction of stellar winds and molecular clouds, circumstellar shells around late-type stars, galactic structure, and the distribution of molecular clouds in spiral galaxies as a function of morphological type. As a result of molecular line studies it is fair to say that our concepts about the nature of dark clouds, stellar formation processes, and interstellar chemistry have changed fundamentally.

The serious study of interstellar molecules is effectively 20 years old. Although Dunham (1937) and Adams (1939, 1941) detected the first molecules (CH, CH⁺, and CN) in interstellar space, the field was for the most part ignored until Weinreb

et al. (1963) discovered the 18cm transitions of OH. Another five years passed before the first polyatomic molecule (NH_3) was detected in late 1968 (Cheung *et al.* 1968) at a wavelength of 1.3 cm. In the meantime more than 56 molecules have been detected, mostly at radio wavelengths, in interstellar space and several rarer isotopic species have been observed; for example $^{12}\text{C}^{16}\text{O}$, $^{13}\text{C}^{16}\text{O}$, $^{12}\text{C}^{17}\text{O}$, $^{12}\text{C}^{18}\text{O}$, and $^{13}\text{C}^{18}\text{O}$ have all been detected in several molecular clouds. A number of heavy, fairly complicated molecules exist in the galaxy; among these are ethyl alcohol ($\text{CH}_3\text{CH}_2\text{OH}$), vinyl cyanide (CH_2CHCN), methyl formate (HCOOCH_3), etc. The heaviest molecule detected to date is HC_{11}N (Bell *et al.* 1982); it is observed in the circumstellar shell of the carbon star IRC+10°216. In tables 1 and 2 are listed the currently known interstellar molecules and their detected rarer isotopic species.

Table 1. Organic interstellar molecules

No. atoms	Molecule	Formula	Spectral regime observed	Rare isotopic species	Notes
2	Carbon monoxide	CO	R, IR, UV	$^{13}\text{C}^{17}\text{O}$, $^{12}\text{C}^{18}\text{O}$, $^{13}\text{C}^{16}\text{O}$, $^{13}\text{C}^{18}\text{O}$	1
	Carbon monoxide ion	CO^+ ?	R		
	Methylidyne radical	CH	R, V		
	Methylidyne radical ion	CH^+	V	$^{13}\text{CH}^+$	
	Cyanogen radical	CN	R, V		
	Carbon monosulphide	CS	R	$^{13}\text{C}^{32}\text{S}$, $^{12}\text{C}^{33}\text{S}$, $^{12}\text{C}^{34}\text{S}$, $^{13}\text{C}^{34}\text{S}$	
	Carbon molecule	C_2	near IR, V		
3	Formylium	HCO^+	R	DCO^+ , H^{13}CO^+ , HC^{18}O^+	2
	Isoformylium	COH^+ ?	R		
	Formyl radical	HCO	R		
	Hydrogen cyanide	HCN	R	DCN , H^{13}CN , HC^{15}N DNC , HN^{13}C , H^{15}NC	
	Hydrogen isocyanide	HNC	R		
	Carbonyl sulphide	OCS	R		
	Ethynyl radical	C_2H	R		
	Thioformyl ion	HCS^+	R		
	4	Formaldehyde	H_2CO	R	
Thioformaldehyde		H_2CS	R		
Isocyanic acid		HNCO	R		
Isothiocyanic acid		HNCS	R		
Cyanoethynyl radical		C_3N	R		
		$\text{C}_3\text{H}?$	R		
5	Methylenimine	CH_2NH	R	H^{13}CCCN , HC^{13}CCN , HCC^{13}CN , DCCCN	4
	Cyanamide	NH_2CN	R		
	Formic acid	HCOOH	R		
	Ketene	$\text{H}_2\text{C}_2\text{O}$	R		
	Cyanoacetylene	HC_3N	R		
	Butadiynyl radical	C_4H	R		
	Protonated carbon dioxide ion	HOCO^+ or			
	Cyanic acid	HOCN	R		
6	Methyl alcohol, methanol	CH_3OH	R	CH_3OD , $^{13}\text{CH}_3\text{OH}$	
	Methylcyanide, acetonitrile	CH_3CN	R		
	Methyl mercaptan	CH_3SH	R		
	Formamide, methanamide	NH_2CHO	R		
7	Methylamine	CH_3NH_2	R		
	Methylacetylene, propyne	CH_3CCH	R		
	Acetaldehyde	CH_3CHO	R		

Continued

Table 1. Continued

No. atoms	Molecule	Formula	Spectral regime observed	Rare isotopic species	Notes
8	Vinyl cyanide, acrylonitrile	H_2CCHCN	R		
	Cyanobutadiyne, cyanodiacetylene	HC_5N	R		
	Methyl formate	$HCOOCH_3$	R		5
	Methyl cyanoacetylene	CH_3CCCN	R		
9	Dimethyl ether, methoxy methane	CH_3OCH_3	R		
	Ethyl alcohol, ethanol	CH_3CH_2OH	R		
	Ethyl cyanide, propionitrile	CH_3CH_2CN	R		
	Cyanoheptatriyne	HC_7N	R		
10	none detected yet				
11	Cyanooctatetrayne	HC_8N	R		
12	none detected yet				
13	Cyanodecapentayne	$HC_{11}N$	R		6

Notes :

1. Identification is based on one line, and is therefore very uncertain (see Erickson *et al.* 1981).
2. Identification is based on one line, and is therefore very uncertain (see Woods *et al.* 1983).
3. C_3H has no measured laboratory spectrum and its energy structure and transition frequencies are uncertain. Although several transitions have been observed which are believed to be due to C_3H , identification with this species cannot be claimed to be certain (personal communication, W.M. Irvine).
4. Three different transitions have been observed but it has not been possible to determine whether the carrier is $HOCO^+$ or $HOCN$ (Thaddeus *et al.* 1981).
5. Identification of this molecule is based on 7 transitions observed during the past year. Announcement of its detection was reported at the January 1983 American Astronomical Society meeting by N. W. Broten, J. M. MacLeod, L. W. Avery, W. M. Irvine, B. Höglund, P. Friberg, and A. Hjalmarsen.
6. This molecule has been observed only in the envelope around the carbon star IRC + 10216. Other molecules observed at infrared wavelengths in the envelope of this star are CH_4 , C_2H_2 , and C_2H_4 .

Table 2. Inorganic interstellar molecules

No. atoms	Molecule	Formula	Spectrum regime observed	Rare isotopic species
2	Hydrogen	H_2	UV, IR	HD
	Hydroxyl radical	OH	R	^{18}OH , ^{17}OH
	Sulphur monoxide	SO	R	^{34}SO
	Nitric oxide	NO	R	
	Silicon monoxide	SiO	R	^{29}SiO
	Silicon monosulphide	SiS	R	
	Nitrogen sulfide	NS	R	
3	Water	H_2O	R	HDO, $H_2^{18}O$
	Hydrogen sulfide	H_2S	R	
	Diazenylium	N_2H^+	R	N_2D^+
	Sulfur dioxide	SO_2	R	$^{34}SO_2$
	Nitroxyl hydride	HNO	R	
	Sodium hydroxide	NaOH	R	
4	Ammonia	NH_3	R	NH_2D , $^{15}NH_3$

Although the field is still very young in comparison with many of the classical areas of study in astronomy, much progress has been made. On the 20th anniversary of the first microwave detection of an interstellar molecule, OH (Weinreb *et al.* 1963), it seems particularly appropriate to examine some of the major contributions and some of the new problems posed by molecular cloud studies to the broader field of astronomy. In fact, molecular line studies already contribute to such a broad spectrum of astronomical research that the whole field cannot be reviewed in any depth within the constraints of a reasonable length. I will therefore only attempt to briefly summarize the following selected topics: molecular cloud chemistry, isotopic abundances, and the distribution of molecular clouds in other galaxies.

2. Chemistry of molecular clouds

We begin this section by considering some aspects of the currently known interstellar molecules listed in tables 1 and 2. First, about equal numbers of organic and inorganic *diatomic* and *triatomic* interstellar molecular species have been identified. There is only one inorganic 4-atom interstellar molecule known (ammonia) and none containing 5 or more atoms. In contrast, there is a wide variety of organic molecules containing 4 or more atoms, the heaviest of which has 13 atoms. The distinction between organic and inorganic, as used here, is simply whether a molecule contains carbon or not. No relationship with living organisms is inferred; that is, organic molecules can be formed in nature independent of living cells. The point of comparing organic with inorganic interstellar molecules is to illustrate the ability of carbon to form long chains and complex molecular structures. In this respect, interstellar chemistry is similar to conventional laboratory chemistry.

Different from laboratory chemistry is the relatively large number of free radicals and ions present in molecular clouds. Radicals are so reactive that they hardly survive long enough to be measured in a typical laboratory situation. Similarly, ions recombine very rapidly to form neutral species and are therefore very difficult to study in the laboratory. In molecular clouds, the combination of very low densities (typically $< 10^3 \text{ cm}^{-3}$) and sources of continuous ionization make it possible for radicals and ions to exist.

From tables 1 and 2, it is also apparent that all the currently known interstellar molecules are composed of only 6–7 of the cosmically most abundant elements. Most molecules are formed from H, C, N, and O; these are also the most abundant elements. He and Ne, although abundant, do not form stable molecules because they have closed electronic shells. A few molecules contain S and Si and only one Na-bearing molecule has been tentatively identified. Na is only about 0.1 as abundant as Si and S. The implication is that as telescopes and receivers become more sensitive molecules containing even less abundant elements will probably be found in interstellar molecular clouds. However, in principle, there is a natural limit beyond which greater instrumental sensitivity will not help. In any given frequency interval, this limit will be reached when the spectral “noise” is determined by overlapping or blending of many weak lines. Presumably most of the overlapping weak lines will be formed by molecules composed of elements having low cosmic abundances. This limit has not been reached. The weakest lines detected so

far with signals $\geq 5\sigma$ above noise have temperatures of the order of a few milli-Kelvins. In the few frequency intervals where the lowest noise spectra have been obtained, it can be stated with confidence that the weak line detection limit set by overlapping lines is $\leq 10^{-3}$ K.

It is also interesting to note what is *not* found in molecular clouds. For example, no radioactive nuclei are found. No amino acids (building blocks of proteins) have been identified. Sensitive searches for two forms of glycine (the simplest amino acid) have been made over a period of ~ 5 years with negative results (Hollis *et al.* 1980; Snyder *et al.* 1983). Perhaps more surprising is the fact that no ring structured molecules have been found despite numerous sensitive searches by several groups (Giguere *et al.* 1973; Simon & Simon 1973; Fertel & Turner 1975; Kutner *et al.* 1980; Myers *et al.* 1980). This is surprising, because ring structured molecules are very stable and once formed are not easily destroyed. One is therefore, led to conclude that for some inexplicable reason stable ring structured molecules either cannot form in molecular clouds or their destruction rates are superfast in comparison to their formation rates. The absence of ring molecules has been used to argue that surface chemistry is probably not of major importance in molecular clouds (Fertel & Turner 1975). Our knowledge of surface chemistry, however, is so sketchy, especially on interstellar grains, that this argument must be considered very tentative. It is obvious from tables 1 and 2 that negative ions have also not been observed. This surely has important chemical implications but has received little attention as yet.

Finally, nearly 300 unidentified lines have been observed in the interstellar medium near the 3mm region of the spectrum alone. These lines are presumably formed by molecules and indicate that many more molecular species exist in space than we have so far been able to identify. Part of the problem with identification lies in the fact that not enough fundamental laboratory measurements are available and part of the problem is that we do not understand enough about interstellar chemistry to be able to predict what molecules should be formed in detectable amounts. It is likely, however, that many of the unidentified lines are due to molecules that are difficult to study in the laboratory, such as radicals, ions, and heavy molecules with complex spectra.

Prior to 1968 it was generally believed that molecules as complex as ethyl alcohol ($\text{CH}_3\text{CH}_2\text{OH}$) or even formaldehyde (H_2CO) could not exist because ultraviolet radiation from stars, which permeates interstellar space, would quickly destroy any complex molecules formed. The lifetime of an H_2CO molecule in this environment would be only a few tens of years (Stief *et al.* 1971), extremely short relative to most astronomical timescales. Formation of polyatomic molecules was considered highly unlikely because of the low densities and temperatures which prevail in interstellar space. A typical atom may collide with another atom once every few months to a year and collisions with atoms other than hydrogen occur less than 10^{-3} times less frequently. It therefore was expected that if a diatomic molecule managed to form, it would probably be destroyed by the ultraviolet radiation field long before a triatomic molecule could be formed. Also typical molecular cloud temperatures are generally too low to overcome most known reaction barriers. It was therefore a great surprise to many when NH_3 was detected toward the centre of our galaxy near the end of 1968 (Cheung *et al.* 1968), and the detection in rapid succession of ever

more complex molecules was a clear signal that something basic was wrong with our understanding of the interstellar medium. Looking back, it is now obvious that several polyatomic molecules could have been detected much earlier (in particular, the 6cm transition of H_2CO) with existing telescopes, but the barrier of not believing in the possibility of their existence had to be broken first. A certain amount of physical intuition regarding which molecules and which transitions to search for was also required.

If it is so difficult to understand how fragile polyatomic molecules can be formed and can survive in the hostile environment of interstellar space, then why are they there? A complete answer to this question cannot be given, but some progress has been made. First, it was almost immediately obvious that interstellar molecules could not be exposed directly to the general interstellar radiation field, because they would be destroyed too rapidly. In the meantime, numerous studies have shown that molecules are not uniformly spread out in space, but are located in higher density clouds. The dust grains in these clouds ($\sim 1\%$ by mass of the gas) act as an ultraviolet filter which prevents destructive stellar radiation from penetrating very deeply into a molecular cloud. Thus the molecules are located in a protective cocoon of dust which allows them to survive once they are formed.

Let us now consider the chemistry of interstellar molecules. This is a complex subject, the rudiments of which were first realized and published in now classical papers by Solomon & Klemperer (1972) and Herbst & Klemperer (1973). Two basic processes are probably operative in molecular clouds; one is catalytic formation (and destruction) on the surfaces of dust grains which we will refer to as surface chemistry and the other is gas phase chemistry.

Surface chemistry involves collisions of atoms and/or molecules with grains. The colliding atoms or molecules must stick to a grain and react with another atom or molecule already on the grain to form a new compound. Either because of the heat of formation, bombardment by a photon, cosmic rays, or collision with another atom or molecule, the newly formed molecule is released into the gas phase where it is observed. H_2 , the most abundant interstellar molecule, is almost certainly formed on grain surfaces. Gas phase formation by radiative association ($\text{H} + \text{H} \rightarrow \text{H}_2 + h\nu$) is highly forbidden since it requires a spin change ($^3\Sigma_u - ^1\Sigma_g$) and involves a repulsive state ($^3\Sigma_u$). H_2 formation on grain surfaces is orders of magnitude faster than any known gas phase reaction (Watson 1975). Sodium hydroxide (NaOH), a recently reported detection, may also be formed on grain surfaces (Hollis & Rhodes 1982).

Surface chemistry in space is not well understood partly because the nature of grain surfaces is not understood. We do not know the composition, geometry, or charge on grain surfaces and until more progress is made in this area surface chemistry is likely to remain obscure. With the major exception of H_2 — and perhaps some metal oxides and metal hydroxides (Duley & Millar 1978)—gas phase reactions are generally expected to dominate surface reaction rates by large factors. Consequently, surface reaction products are likely to be further processed by gas phase reactions in any case. A very important effect that the presence of grains almost certainly has on the chemistry, even in the gas phase, is that they tie up major fractions of certain elements such as Ca, Ti, Fe, Mg, etc. thereby altering drastically the gas phase abundances available for a chemical network.

Gas phase chemistry has received more attention because it is a more tractable problem and our understanding in this area is certainly deeper. Because of low densities, low temperatures, and the relative abundances of the elements in molecular clouds, one can identify several important general constraints on interstellar gas phase chemistry. These are : (i) only two-body (binary) collisions need be considered, 3-body collisions being too infrequent to be important; (ii) only exothermic reactions with no activation energy barrier need be considered; and (iii) reactions involving the most abundant species will generally dominate. For example, if a given molecule reacts at a reasonable rate with H_2 , one can be reasonably certain that the main reaction path will be with H_2 rather than some other molecule because of the overwhelming abundance of H_2 ; or, if a molecule cannot react with H_2 but readily reacts with CO, then one can assume that CO will be the dominant destruction path since it is the second most abundant molecule after H_2 . Also, because of the infrequent interactions of a typical molecule in space, we know that interstellar chemistry must be exceedingly efficient; a reaction from almost every collision is required to account for the observed abundances.

Basic papers on interstellar gas phase chemistry are Solomon & Klemperer (1972); Herbst & Klemperer (1973, 1976), Watson (1975, 1976) and Black & Dalgarno (1977). Several later chemical models (some of which include time dependence) are Mitchell *et al.* (1978), Iglesias (1977), Suzuki (1979), Prasad & Huntess (1980), and Graedel *et al.* (1982). In the following, I will try to summarize the basic ideas and leave the details for the reader to glean from the above references.

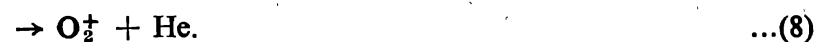
In the central region of dark (opaque) molecular clouds, gas phase chemistry is powered by cosmic ray (CR) ionization of H_2 and He. Cosmic rays with energy ≥ 100 MeV can penetrate even the largest molecular clouds. The cosmic ray ionization rate per particle is $\sim 10^{-17}$ ionizations per second. Although incredibly small, enough energy is deposited by this process to drive an extensive chemical network. The small fraction of H_2^+ formed by CR ionization then reacts with H_2 to form H_3^+ via



Since H_3^+ does not react with H_2 , it is believed to be abundant and a key component in interstellar chemistry because it can react with less abundant atoms and molecules to form heavier ions such as



The detection of HCO^+ and N_2H^+ has given strong support to the scheme described here. He^+ , the next most abundant ion produced by CR ionization, reacts very slowly with H_2 and primarily provides an efficient mechanism to produce C^+ , N^+ , and O^+ via reactions such as



The ions so produced can then react with species of lower ionization potential, forming in the process a great variety of both neutral and ionic molecular species. Positive ions and neutral atomic or molecular species generally have very small or no activation energy barrier and proceed rapidly (the Langevin rate $\approx 1-2 \times 10^{-9} \text{ cm}^3 \text{ s}^{-1}$), independent of temperature. Ion-molecule reactions, therefore, are believed to dominate gas phase reactions in molecular clouds.

The ion-molecule theory has been very successful in accounting for the relative abundances of the simplest interstellar molecules and ions, particularly HCO^+ and N_2H^+ . Whether the heavier interstellar molecules (> 4 atoms) can be produced with adequate abundances and in the right proportions by the ion-molecule scheme still remains to be seen. Also the presence of the key ion, H_3^+ , has yet to be established because it has no transitions at radio wavelengths; several searches have been made, however, for its deuterated species H_2D^+ without success (Angerhofer *et al.* 1978). The transition searched was not an intrinsically strong one and the calculated transition frequency had a relatively large uncertainty, so the limits established for H_2D^+ are not particularly stringent.

Douglas (1977) has suggested that interstellar cyanopolyynes could be formed by the destruction of heavy carbon chains, particularly those with alternating single triple bands (*i.e.* the reverse of synthesis from light to heavy as prescribed in the ion-molecular theory). He has also argued that these chains (≥ 15 C-atoms) might also be responsible for many of the unidentified diffuse interstellar bands observed in optical spectra for many years. The possible presence of very long carbon chains as well as other complex species is still not resolved.

Duley *et al.* (1980) have proposed that sulphur-bearing interstellar molecules may be formed via surface reactions since these species (particularly SH_2) cannot be produced with their observed abundances under typical cloud conditions by ion-molecule chemistry. Hartquist *et al.* (1980) argue that substantial abundances of sulphur-bearing molecules may be formed in shocks (transient, non-equilibrium, gas-phase chemistry). Temperatures and densities are increased in shocked regions resulting in enhanced reaction rates and the possibility of endothermic reactions. Another possible problem for ion-molecule chemistry is the tentative detection of CO^+ by Erickson *et al.* (1981) because this ion cannot be produced with its inferred abundance by conventional ion-molecule chemistry. CO^+ was identified on the basis of a single line and must be confirmed with observations of other transitions before this need be considered a serious problem for ion-molecule chemistry.

Interstellar chemistry is not yet understood well enough to predict with certainty the presence of a particular complex molecule. Perhaps the most intriguing problem of all is how molecules manage to exist in detectable abundances in cold opaque clouds at all. After a period $\sim 10^6$ yr practically all molecules are expected to have been adsorbed onto grain surfaces (Iglesias 1977). Observations of the $3.07 \mu\text{m}$ "ice" feature in several opaque molecular clouds (Merrill, *et al.* 1976; Harris *et al.* 1978; Churchwell & Koornneef 1984) strongly support the idea that grains in the core of opaque clouds develop substantial mantles at the expense of gas phase atoms and molecules. Even in these clouds, however, gas phase molecules are abundant, implying that the grains only manage to capture a small percentage of the free molecules at any given time. This is not understood.

Only chemistry in opaque clouds has been discussed here. In diffuse clouds and the extremities of opaque clouds photoionization processes, radiative recombinations, and dissociative recombination reactions become much more important than in opaque clouds due to increased ultraviolet radiation densities and increased electron densities. Much effort has also been invested in the study of circumstellar molecular shells around cool stars (see for example Goldreich & Scoville 1976 and Morris 1980). Also it has become clear in the past few years that molecular clouds undergo shocks due to imfringement of stellar winds, supernovae, HII regions, and cloud-cloud collisions. Modifications of relative molecular abundances in shocked regions occur because endothermic reactions are possible. Gas-phase chemistry in shocked regions has been considered by Iglesias & Silk (1978), Elitzur & Watson (1978), Lada *et al.* (1978), Elitzur (1980), Hartquist *et al.* (1980), DeNoyer & Frerking (1981) and Herbst & Knudson (1981) among others. Watson & Walmsley (1982) have made a careful comparison of abundances in shocked versus unshocked regions and in warm versus cold clouds. They conclude that although a few anomalies occur between observation and theory, there are no discrepancies where it is "beyond doubt that an alternative to ion-molecule mechanisms is necessary".

3. Isotopic abundances

Isotopic abundance ratios are particularly important because they provide direct clues to the extent of thermonuclear processing of interstellar material and therefore to the evolution of the galaxy. The possibility of obtaining isotopic abundance ratios from molecular lines was recognized almost simultaneously with the detection of interstellar molecules. Determinations of reliable abundance ratios, however, have proved to be more complicated than originally expected and considerable effort has been invested in understanding the problems involved. A major problem for some species (particularly deuterium and ^{13}C) is the extent to which chemical fractionation occurs in molecular clouds. That is, do isotopically substituted molecules occur in direct proportion to the relative abundances of their isotopes (*e.g.* does $\text{DCN}/\text{HCN} = \text{D}/\text{H}$?)? Another important problem is recognition of, and correction for, radiative transfer effects, and departures from thermodynamic equilibrium. Some reviews of isotopic abundances and related problems are: Bertojo *et al.* (1974); Wannier *et al.* (1976); Winnewisser *et al.* (1979); Penzias (1980); and Wannier (1980). Because of these very good reviews I will only briefly discuss the salient features of the problems involved and then try to summarize the results as they currently stand.

A. Chemical fractionation

1. DEUTERIUM

Since deuterium (D) can be destroyed at relatively low temperatures in stellar interiors, matter processed by stars is expected to be devoid of deuterium. We therefore expect the deuterium present in the interstellar medium today to have been produced originally in the big bang. Its present abundance should, therefore, be a measure of how much material has *not* been processed through stars during the lifetime of the galaxy.

The average D/H abundance ratio within a few hundred parsecs of the sun is $\sim 2 \times 10^{-5}$ (York & Rogerson 1976; Laurent *et al.* 1979 and references therein).

By contrast, the line intensity ratio of deuterated-to-hydrogenated polyatomic molecules is typically $\geq 10^{-3}$ in warm molecular clouds and as large as ~ 1 in a few cold molecular clouds (Hollis *et al.* 1976; Guelin *et al.* 1977). Obviously, chemical fractionation of deuterated molecules is very important in molecular clouds.

The primary source of D^+ is believed to be the resonant charge exchange reaction



which has a rate coefficient of $10^{-9} \text{ cm}^3 \text{ s}^{-1}$. H^+ is formed by cosmic ray ionization. HD may then be formed via



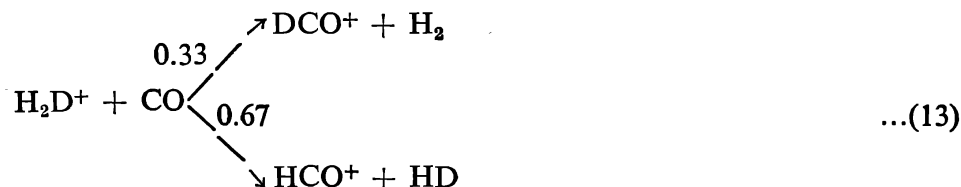
Enhancement of heavier deuterated species may follow via two exothermic reactions



and perhaps



The exothermicities in reactions (11) and (12) restrict the reverse (right to left) rates particularly in cold clouds, causing enhancements of the deuterated species on the right by factors of $n(H_2D^+) \exp(\Delta E_1/kT)$ and $n(CH_2D^+) \exp(\Delta E_2/kT)$ if chemical equilibrium holds; $\Delta E_1/k \simeq 80 \text{ K}$ (Adams & Smith 1981b) and $\Delta E_2/k \simeq 300 \text{ K}$ (Blint *et al.* 1976). These enhancements may then be passed on to other deuterated species by reactions such as



and



followed by

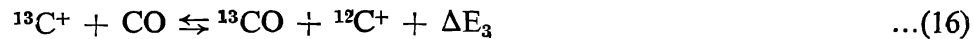


As pointed out by Watson & Walmsley (1982), the exothermicity in reaction (11) is apparently too low to account for enhancements of H_2D^+ by factors much greater than 10–100 in warm clouds or greater than ~ 1000 in cold clouds ($T \simeq 10 \text{ K}$). However, ΔE_1 may be substantially larger than 80 K because the zero-point rotational energy of H_3^+ has not been included. Watson & Walmsley (1982) conclude that reaction (11) cannot be excluded as the basic deuteration mechanism in warm molecular clouds, although alternatives should not be ruled out. In particular, species which are not direct “descendants” of H_2D^+ or CH_2D^+ , such as HDO and NH_2D , are not yet understood. The basic observational result is that deuterated molecules are strongly chemically fractionated with the degree of fractionation increasing as cloud temperature decreases. This is expected, and understood in a general way from ion-molecule chemistry because of substantial exothermicities between hydrogen and deuterium.

A summary of the DCN/HCN and DCO⁺/HCO⁺ ratios as of 1976 were tabulated by Winnewisser *et al.* (1979). Wannier (1980) has summarized the results on the DCN/HCN, DCO⁺/HCO⁺, and NH₂D/NH₃ ratios in warm molecular clouds as a function of galactic radius. He claims that a radial D/H gradient exists in the sense that D/H is low in the galactic centre and increases outward. The difference, however, between the galactic centre and $R = 13$ kpc is only a factor of 4–5 (from DCN/HCN, for which the best statistics are available); this is small relative to fractionation effects. Further, the statistics are poor, values for only ten clouds are tabulated between $0 \leq R \leq 13$ kpc, and the sensitivity of deuterium fractionation to temperature severely complicates the derivation of D/H ratios.

2. ¹³C FRACTIONATION

The importance of ¹³C enhancement via the reaction



was first pointed out by Watson *et al.* (1976). The exothermicity of this reaction is only 35 K, so it is important only in relatively cool clouds [*e.g.* at $T \leq 50$ K, $\exp(\Delta E_3/kT) \geq 2$]. Further, reaction (16) requires an abundant supply of ¹³C⁺ and CO in the same volume to be effective. Such conditions occur in regions where the molecular gas is exposed to near-ultraviolet radiation ($h\nu \lesssim 11.3$ eV) such as the vicinity of embedded hot stars and at cloud peripheries which are exposed to the general interstellar radiation field. In these regions, models by Langer (1977) and Liszt (1978) show that ¹³CO/¹²CO may be enhanced by a factor of 8 or so over the ¹³C/¹²C abundance ratio. The enhancement factor is obviously a sensitive function of the temperature structure of molecular clouds, particularly in the regions where reaction (16) is important. Clear cut observational information on the temperature structure of molecular clouds is actually rather limited. Langer *et al.* (1980) find from an analysis of the $J = 1-0$ and $J = 2-1$ transitions of CO, ¹³CO, C¹⁸O, and ¹³C¹⁸O that ¹³CO/¹²CO is enhanced by a factor of ~ 2 in the peripheries of dark clouds (assuming that ¹³C/¹²C is given by ¹³C¹⁸O/¹²C¹⁸O). They find that ¹²C/¹³C = 60 ± 5 ; the terrestrial value is 89.

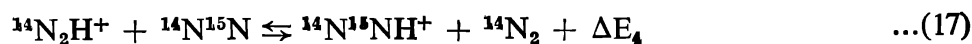
Wannier (1980) argues that ¹³C fractionation in CO is probably unimportant in “dense cores of giant clouds” (where there is essentially no UV radiation and $\text{C}^+/\text{CO} \ll 1$), and therefore, if transfer problems are properly accounted for, molecular line ratios from these regions should give a correct ¹²C/¹³C abundance ratio. He has tabulated all molecules for which ¹²C and ¹³C species have been measured toward cores of giant clouds having broad lines (CO, H₂CO, HCO⁺, HCN, HC₃N, OCS, CS, and NH₂CHO). He concludes that: (i) the average ¹²C/¹³C ratio is 60 ± 8 (*i.e.* ¹³C is enhanced by about a factor of 1.5 on average relative to its solar value); (ii) there is no evidence for a ¹²C/¹³C gradient with galactocentric radius in the range $5 \leq R < 13$ kpc; and (iii) the ¹²C/¹³C ratio in the galactic centre is different from that in the disc in the sense that ¹³C appears to be enhanced by about a factor of 3 over that in the disc (or a factor of 4–5 relative to the terrestrial value). It is prudent to caution that the scatter in ¹²C/¹³C at all galactocentric radii is large ($>$ a factor of 2) and a factor of ~ 1.5 enhancement over the terrestrial value of ¹³C/¹²C in the galactic disc is not large relative to possible chemical fractionation effects. This is strongly emphasized by a recent study of CO emission (¹²C¹⁶O, ¹³C¹⁶O and ¹²C¹⁸O)

from the two giant molecular clouds NGC 2264 and W3 (OH) by Penzias (1983). He finds that ^{13}C chemical fractionation in CO cannot be ignored even in giant molecular clouds; he finds the $^{12}\text{C}/^{13}\text{C}$ abundance ratio to be 100 ± 14 .

Since CO suffers both from possible transfer effects and chemical fractionation effects it is important to ask what other molecules give the $^{12}\text{C}/^{13}\text{C}$ abundance ratio. Wannier (1980) has listed several other molecules for which both the ^{12}C and ^{13}C species have been measured and claims that they are basically in agreement with the results of the CO data. Recently, however, Henkel *et al.* (1982) have analyzed the H_2 $^{12}\text{CO}/\text{H}_2$ ^{13}CO intensity ratios in more than 20 galactic molecular clouds taking particular care to correct for radiative transfer effects (photon trapping). They found a mean abundance ratio of H_2 $^{12}\text{CO}/\text{H}_2$ $^{13}\text{CO} = 80 \pm 7$ in the solar neighbourhood (distances ≤ 2 kpc from the sun) and concluded that "(i) for the carbon isotopes, the solar system value is typical for the interstellar medium near the sun; and (ii) there has been little or no ^{13}C enrichment in the vicinity of the sun since the formation of the solar system". They also claim that the H_2 $^{12}\text{CO}/\text{H}_2$ ^{13}CO column density ratio systematically increases by about a factor of two from a galactocentric radius of 4 kpc to 13 kpc. Their data are shown in figure 1 (top); a similar plot from Wannier (1980) is shown in figure 1 (bottom). These plots clearly demonstrate the level of uncertainty we are dealing with and the difficulty of establishing whether a $^{12}\text{C}/^{13}\text{C}$ gradient exists. Probably the only thing one can say with certainty at this point is that a lot more careful observational and theoretical work will have to be done before a more definite statement can be made about galactic isotopic abundance gradients. On the other hand, the case seems quite strong that within a radius of ~ 2 kpc from the sun the $^{12}\text{C}/^{13}\text{C}$ abundance ratio is about the same as the solar value.

B. Abundances of other isotopes

The data on isotopes of oxygen, nitrogen, silicon and sulphur are tabulated and summarized by Wannier (1980). These data are less extensive than those for ^{13}C and conclusions drawn from them are correspondingly less certain. Chemical fractionation reactions are not expected to be important for these atoms and it is generally presumed that if corrections are made for line formation and radiative transfer effects, the relative intensities give the correct relative abundances. The results as they stand at present are as follows. $^{16}\text{O}/^{18}\text{O}$ is approximately solar throughout the galactic disc, but ^{18}O appears to be enhanced by ~ 2 in the galactic centre over its value in the disc. $^{18}\text{O}/^{17}\text{O} \sim 3.2$ throughout the disc, about 60% lower than the solar value. A possible mechanism for enhancing ^{15}N in N_2H^+ has been proposed by Adams & Smith (1981a). They have measured rates for the reaction



at 292 K and at 80 K and find that $\Delta E_4/k = 9 \pm 3$ K. Thus only in very cold clouds is ^{15}N enhancement in N_2H^+ likely to be important; they find that in chemical equilibrium ^{15}N could be enhanced in N_2H^+ by a factor of 2.5 relative to N_2 at 10 K. No convincing observational test of this possibility has been made since no ^{15}N isotope of N_2H^+ has been detected. Establishing this will be extremely difficult because an

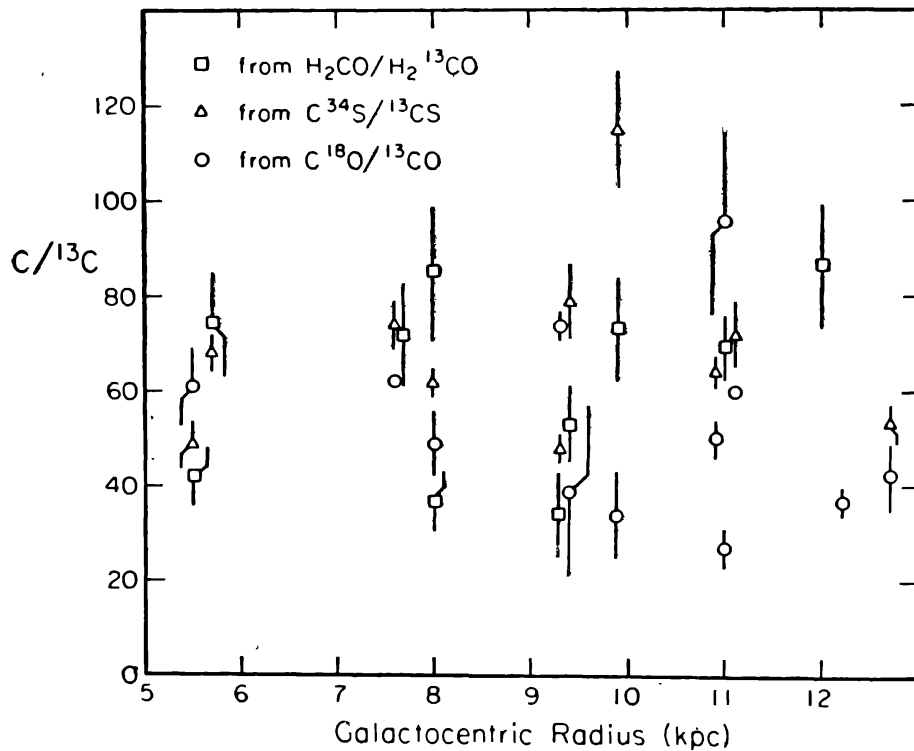
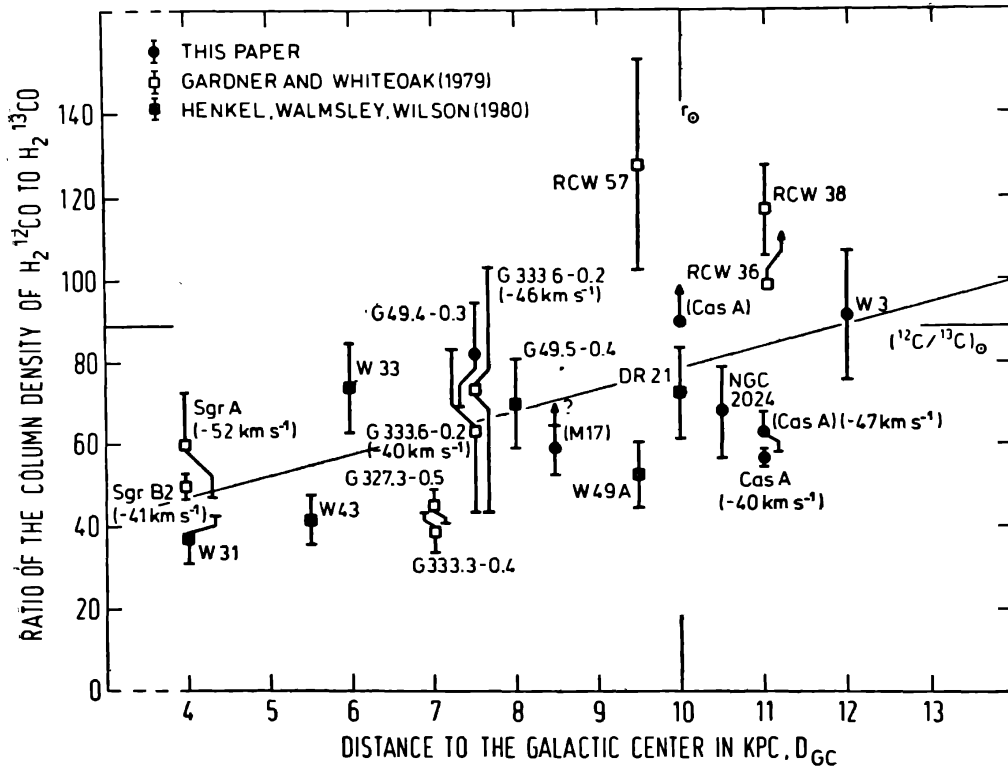


Figure 1. The galactocentric distribution of $^{12}\text{C}/^{13}\text{C}$ inferred from various molecules. Top — $\text{H}_2^{12}\text{CO}/\text{H}_2^{13}\text{CO}$ from Henkel *et al.* (1982); Bottom—from Wannier (1980).

enhancement by a factor or ~ 2 for ^{15}N is a small perturbation on its very low abundance (1/272) relative to ^{14}N . According to Wannier (1980), $^{14}\text{N}/^{15}\text{N}$ is about the same as the solar value (1/272) in the disc, but ^{15}N is apparently underabundant in the galactic centre by < 0.5 the solar value. To within the uncertainties $^{29}\text{Si}/^{30}\text{Si}$, $^{34}\text{S}/^{33}\text{S}$, and $^{32}\text{S}/^{34}\text{S}$ are the same as the solar ratios. $^{28}\text{Si}/^{29}\text{Si}$ appears to be only $\sim 1/2$ the solar value. The reader is referred to Wannier (1980) for problems and precautions concerning these ratios.

4. Molecules in other galaxies

In table 3 the molecules detected in other galaxies are listed along with the galaxies in which they have been observed. This list is far less extensive than tables 1 and 2 as one would expect because only the intrinsically strongest lines can be detected at extragalactic distances with currently operational telescopes. This situation will no doubt change very rapidly when the Nobeyama 45-metre and the IRAM 30-metre millimeter-wave telescopes become fully operational. Nonetheless, the emerging picture is that other spiral galaxies have molecular clouds similar in chemical complexity and other properties to those in our own galaxy. In our own galaxy, CO is second only to H_2 in abundance, but H_2 is homonuclear and consequently has no observable rotational spectrum. Thus CO produces by far the strongest and most widespread emission of any known molecule. The only exceptions are a few intense but very localized H_2O and OH maser sources. This is also the case in other

Table 3. Molecules detected in other galaxies

Molecule	Galaxies	References
H_2	NGC 1068	1
	OQ 172	2, 3
CO	NGC 3227, NGC 4051, M31, M81, IC 342	4, 5, 6, 7, 8, 9
	NGC 342, NGC 6946, NGC 253, M82, M51, M101	10, 11, 12
	NGC 5232, NGC 1068, Maffei 2, M63, LMC	
	NGC 3627, NGC 3628, and others.	
OH	M82, NGC 253, NGC 5128, NGC 4945, LMC	13, 14, 15, 16, 17, 18, 19
CH	LMC, NGC 4945, NGC 5128, NGC 253 (?)	20
HCO^+	NGC 253, M82	21, 22
HCN	M82, NGC 253	22, 23
NH_3	IC 341, NGC 253	24, 25
H_2O	M33, IC 342, NGC 253, NGC 4945	26, 27, 28, 29
H_2CO	M82, LMC, NGC 5128, NGC 253, NGC 4945	30, 31, 32, 16, 33

References: 1. Thompson *et al.* (1978); 2. Varshalovich & Levshakov (1978); 3. Levshakov & Varshalovich (1979); 4. Bieging *et al.* (1981); 5. Emerson (1978); 6. Combes *et al.* (1977); 7. Morris & Lo (1978); 8. Rickard *et al.* (1977); 9. Rickard *et al.* (1977); 10. Rickard *et al.* (1975); 11. Solomon & deZafra (1975); 12. Huggins *et al.* (1975); 13. Rieu *et al.* (1976); 14. Weliachew (1971); 15. Gardner & Whiteoak (1975); 16. Gardner & Whiteoak (1976a); 17. Whiteoak & Gardner (1973); 18. Whiteoak & Gardner (1975); 19. Whiteoak & Gardner (1976a); 20. Whiteoak & Gardner (1980); 21. Rickard & Palmer (1981); 22. Stark & Wolf (1979); 23. Rickard *et al.* (1977); 24. Martin & HO, (1979); 25. Martin *et al.* (1982); 26. Churchwell *et al.* (1977); 27. Huchtmeier *et al.* (1978); 28. Huchtmeier *et al.* (1980); 29. Lepine & Dos Santos (1977); 30. Graham *et al.* (1978); 31. Whiteoak & Gardner (1976b); 32. Gardner & Whiteoak (1976b); 33. Gardner & Whiteoak (1974).

galaxies. While one is happy to simply detect other molecules toward the nucleus (or toward a bright H II region in the case of H₂O) of a spiral or irregular galaxy, CO can generally be mapped over major portions of the discs of the same galaxies. CO is the primary tool used to study molecular properties and distributions in other galaxies. With larger, more sensitive mm-wave telescopes less abundant molecules will certainly receive more attention, but, if our galaxy is any guide, none are as widely distributed as CO and therefore are unlikely to replace CO as the global tracer of molecular gas in other galaxies.

The motivations for studying molecules in other galaxies are much the same as those for studying other sources of radiation. The primary consideration is that one can see directly, with little ambiguity, where the radiation originates within the galaxy if it is a face-on spiral. The rotation curve can be obtained if a spiral has some inclination to the plane of the sky. Thus one can indeed study the distribution of molecular gas within a galaxy. The observed distribution can be compared with other distributions such as blue light, H I emission, H II regions, positions of spiral arms, etc. An important goal of such studies is to determine whether systematic differences with morphological type occur, and if so, can we learn more about the fundamental reasons for the different morphologies of galaxies and galaxy evolution ?

A fundamental result from the study of galactic molecular clouds is that they are the sites of star formation. Recent aperture synthesis and very long baseline interferometry (VLBI) have shown that the 1.3cm H₂O maser and the type I (main line) 18cm OH masers are almost always located very near a compact continuum or infrared source believed to be powered by a relatively massive star in the process of formation (Turner 1982; Genzel *et al.* 1978). The H₂O masers, in fact, are composed of many very small, spatially separate, velocity components clustered around either an ultracompact radio continuum source or compact infrared source (see figure 2). Proper motions of the H₂O masers in Orion, measured using VLBI techniques (Genzel *et al.* 1981), clearly show that they are expanding away from a point located within 5 arcsec of the infrared source no. 2 in the Orion molecular cloud. H₂O masers observed in other galaxies show very narrow, multiple velocity profiles exactly analogous to those observed in galactic molecular clouds (see figure 3). It therefore seems a safe bet that we are observing the same phenomenon in these clouds as in our own galaxy. Studies of clouds in our own galaxy lead us to expect that other galaxies having substantial masses of molecular gas should also be undergoing rapid star formation and that the position of H₂O masers pin point the location of current massive star formation. Strong support for the expectation that the star formation rate and the mass of molecular gas should be closely coupled has been obtained by Young & Scoville (1982a, b, c), Scoville & Young (1982), Young *et al.* (1982) and Solomon *et al.* (1982). They find that the ratio of integrated CO line intensity ($K \text{ km s}^{-1}$) and the blue surface brightness ($B \text{ mag arcsec}^{-2}$) is constant over the discs of at least twelve galaxies for which detailed data exist [see figures 4 and Young & Scoville (1982b) for a partial summary]. They find $M_{\text{H}_2}/L_B = 0.17 \pm 0.08 M_{\odot}/L_{\odot}$ in Sc galaxies over two orders of magnitude in L_B . Assuming that the CO intensity is proportional to the mass of H₂ and its blue light is produced by recently formed hot stars, they claim that the star formation rate per nucleon is constant in Sc galaxies. Particularly interesting is the comparison of the

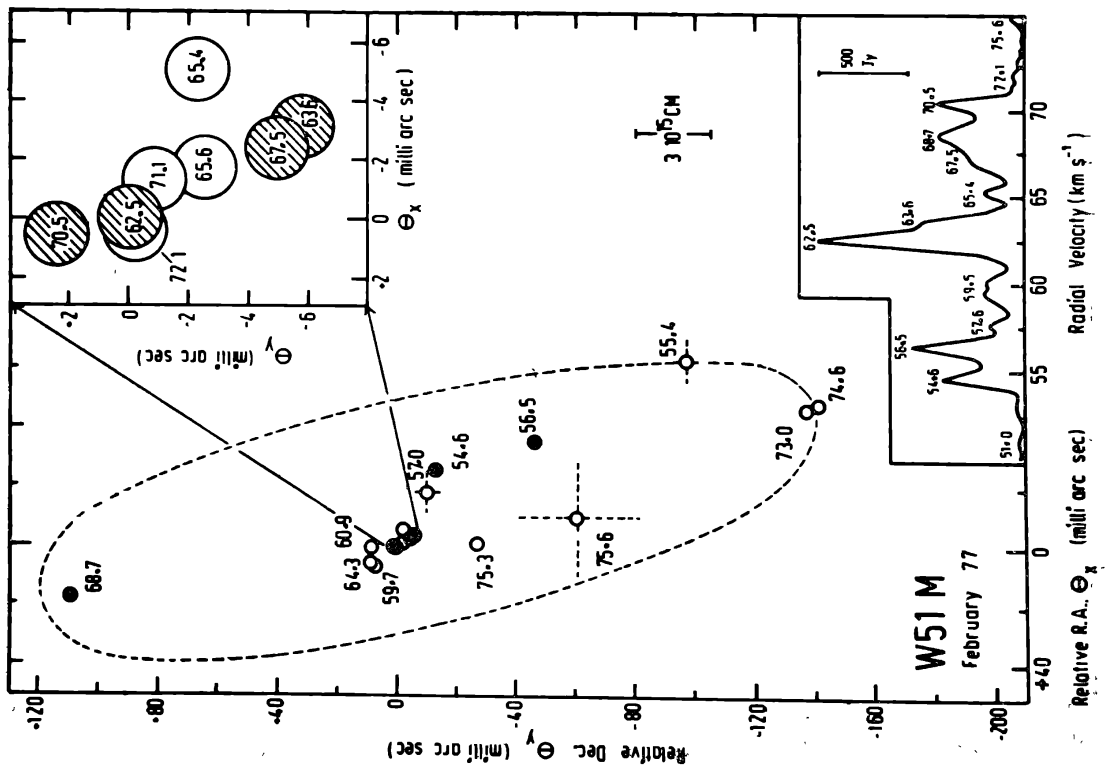
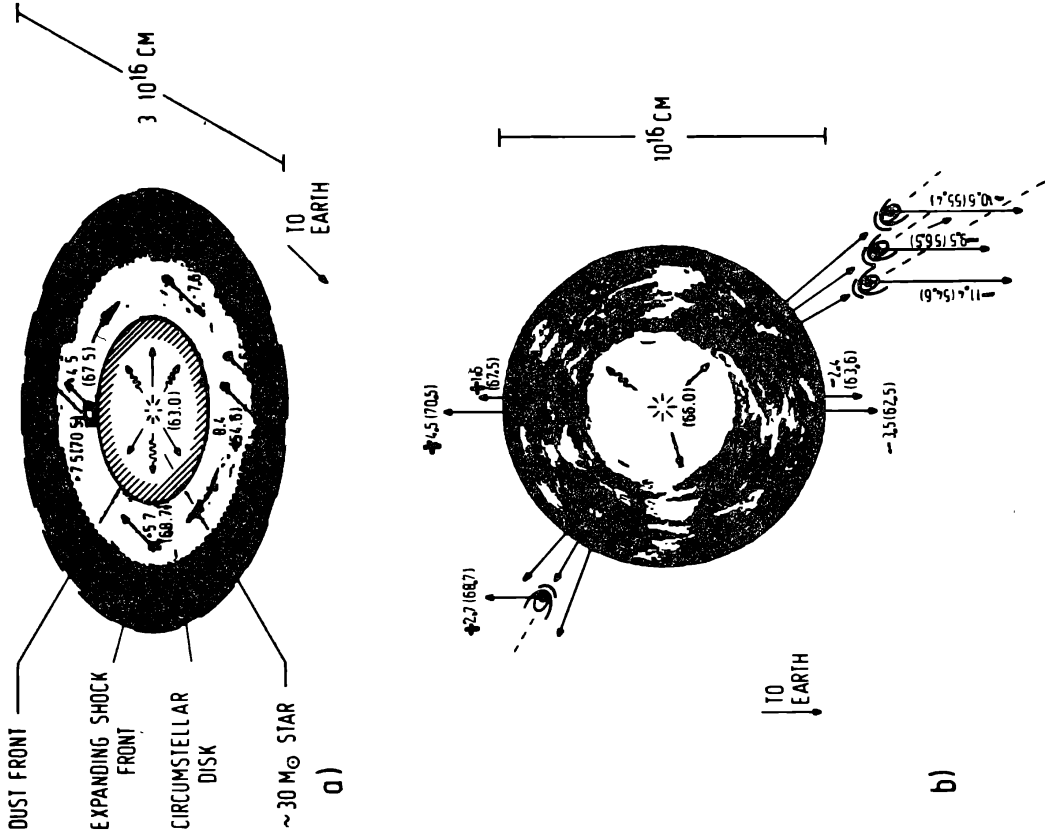


Figure 2. (Left) Very long baseline interferometric positions of strong, low-velocity H_2O maser emission in W51 Main in 1977 February (Genzel *et al.* 1978). The inset (upper right) is an enlargement of the intense maser group near the centre of the figure. Relative positional uncertainties are indicated by the size of the circles. Labels are LSR velocities. Error bars larger than the general mean are indicated by dashed crosses. The linear scale is for an assumed distance of 8 kpc. The inset at the bottom is the single-dish spectrum of the low velocity emission obtained at Effelsberg 1977 February. The dashed ellipse is the region interpreted as being a circumstellar disc. (Right) Kinematic models of W51 M. The H_2O emission is presumed to arise in a dense, expanding disc or shell around a massive star. The labels give the line-of-sight velocities relative to the star; observed LSR velocities are in parenthesis (Left figure).

Model (a) an expanding and rotating disc observed nearly edge-on. The radial velocity of the star is 63 km s^{-1} , the expansion and rotation velocities are both $\sim 7 \text{ km s}^{-1}$. The H_2O features at $\sim 0 \text{ km s}^{-1}$ could come from either the front or back, of the disc, slightly outside the shock front. High velocity features could be blown out at the poles of such a disc

Model (b) an expanding shell, viewed perpendicular to the line of sight to the earth. The star, with $V_{\text{LSR}} \sim 66 \text{ km s}^{-1}$, has directional flares from time to time, which drive higher-velocity material through holes or tunnels in an otherwise stable shell. The shell expands at a velocity of 3 km s^{-1} (after Genzel *et al.* 1978).

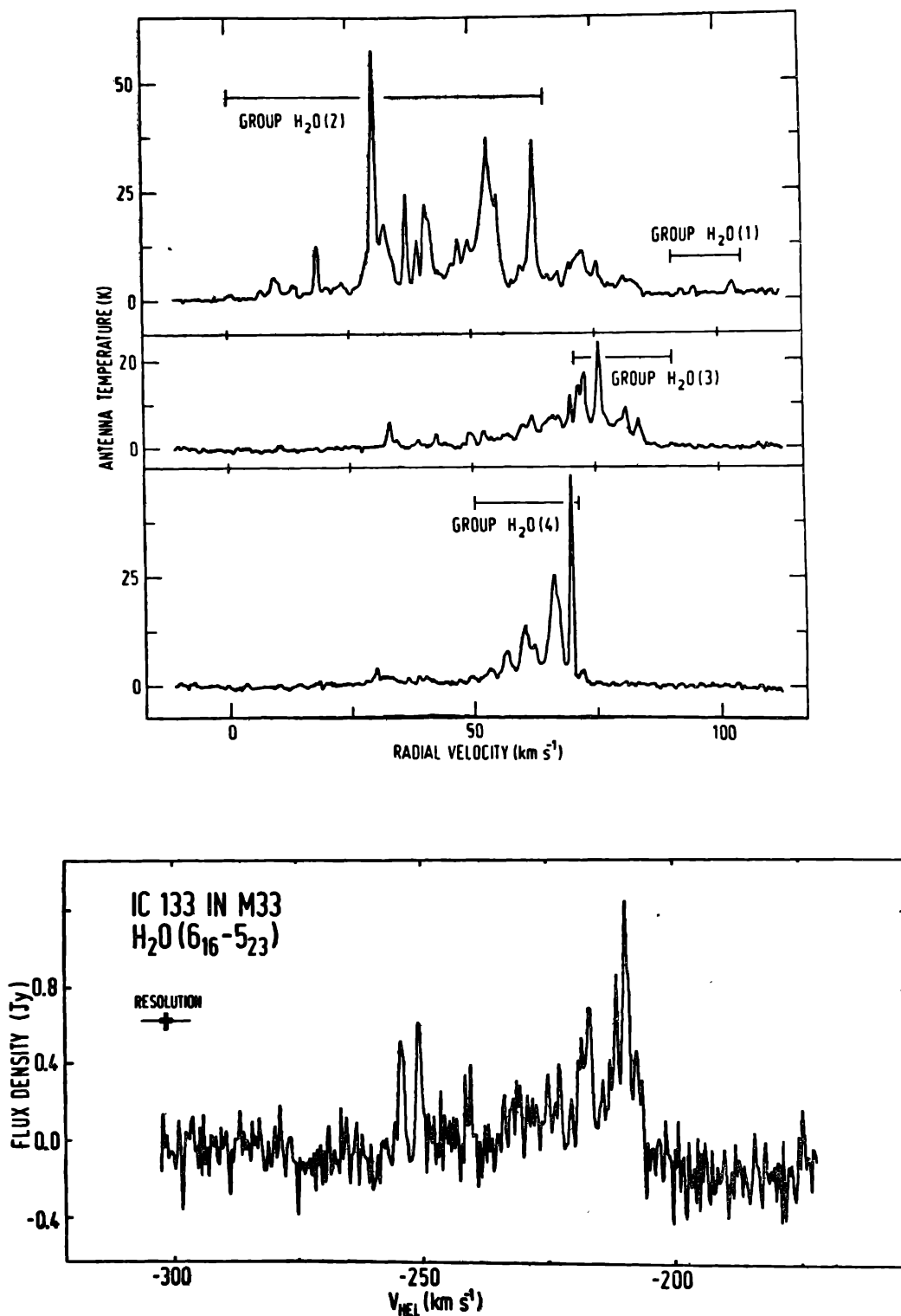


Figure 3. (Top) H₂O maser profiles toward three different positions (4 groups of maser sources) in the massive galactic molecular cloud Sgr B2 (from Genzel *et al.* 1976). (Bottom) H₂O maser profiles toward the molecular cloud associated with the H II region IC 133 in M33 (Churchwell *et al.* 1977). This was the first detection of H₂O outside our galaxy.

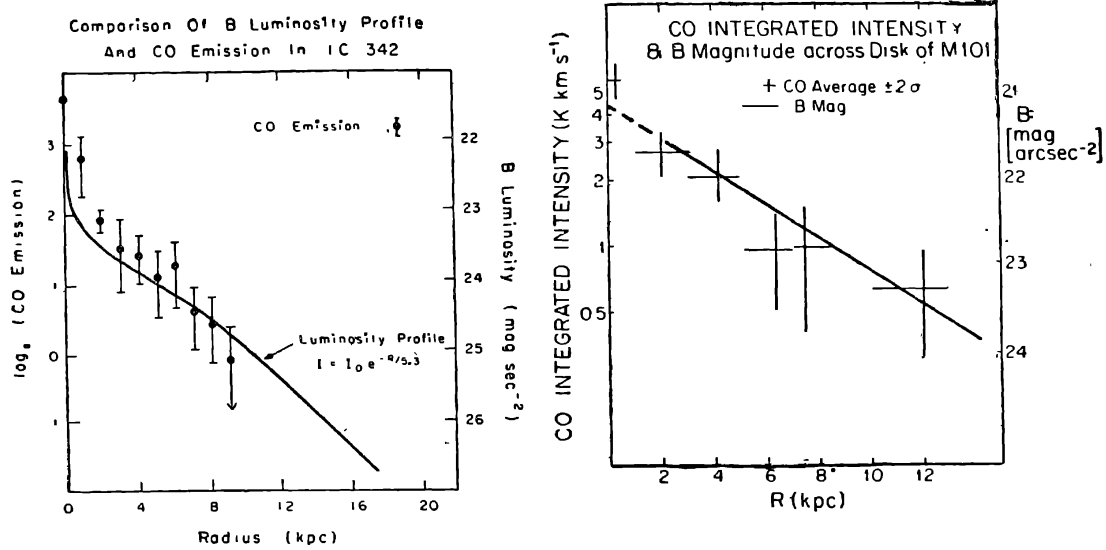


Figure 4. (Left) Comparison of CO integrated line intensity (filled dots) with the surface brightness of blue light (solid curve) in IC 342 (Young & Scoville 1982). (Right) A similar plot for M101 (Solomon *et al.* 1983).

radial distributions of CO, far-infrared, stellar, and radio continuum emissions and the derived H_2 and H I surface densities in M51 (Scoville & Young 1983). Here the stellar light, the radio continuum, far-infrared emission and the molecular surface density are all rather similar, illustrating the very close correlation of molecular gas and stars, particularly the young hot stars. There is, of course, some uncertainty in converting CO intensities to H_2 masses because the abundance ratio of CO/ H_2 is not well established; it may not be constant with radius within galaxies, and the CO lines are probably optically thick so even the conversion from intensity to total CO column density is problematic. Nonetheless, the basic conclusions, even allowing for uncertainties in the molecular masses, are probably correct.

In all galaxies so far mapped there is a strong decrease in CO intensity with increasing galactocentric radius (see figure 5), implying a corresponding decrease in H_2 mass and in the formation rate of massive stars. Comparison of the inferred radial surface densities of H_2 and H I shows a general pattern in the galaxies so far studied (mostly Sc). In the central few kiloparsecs (generally $R < 8$ kpc), H I is low and H_2 is the dominant form of interstellar material; at radii $R > 8-10$ kpc the H I and H_2 surface densities cross and H I apparently becomes the dominant form of interstellar matter in the outer regions of galaxies. The H I radial distribution is generally very broad, almost flat in the region of maximum surface density. The maximum H I surface density (at large radii) is typically a factor of 0.1 or less than that of the maximum H_2 surface density (at small radii). These points are illustrated in figures 6(a) and (b) where the radial distributions of H I and H_2 surface densities are plotted for the Sc I galaxies M101 and M51. To what extent this is characteristic of all spirals is not clear. Unlike the other spirals so far studied in some detail, M31 (Sb) is dominated throughout by H I (Stark 1980; Linke 1982). No CO emission has been detected from NGC 3623 (Sa), but its neighbours NGC 3627 (Sb) and NGC 3628 (Sbc) have been partially mapped in CO emission (Young *et al.* 1983).

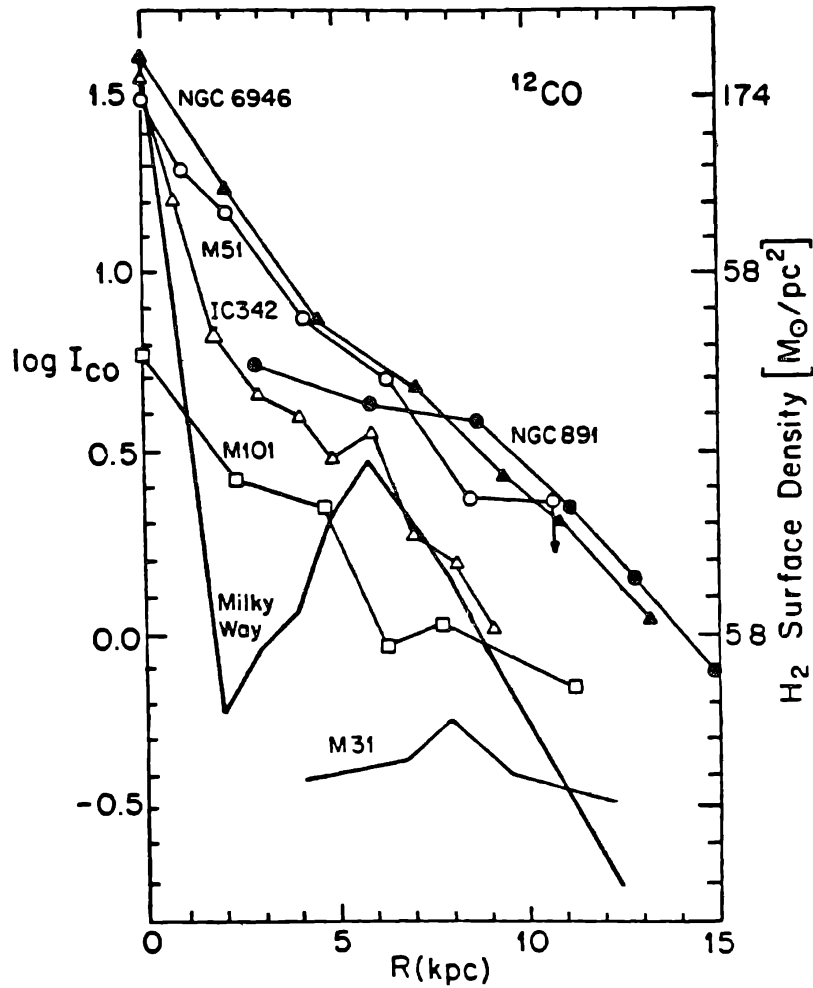


Figure 5. The galactocentric radial distributions of integrated CO intensity and inferred H_2 surface density in seven galaxies. (Solomon 1983).

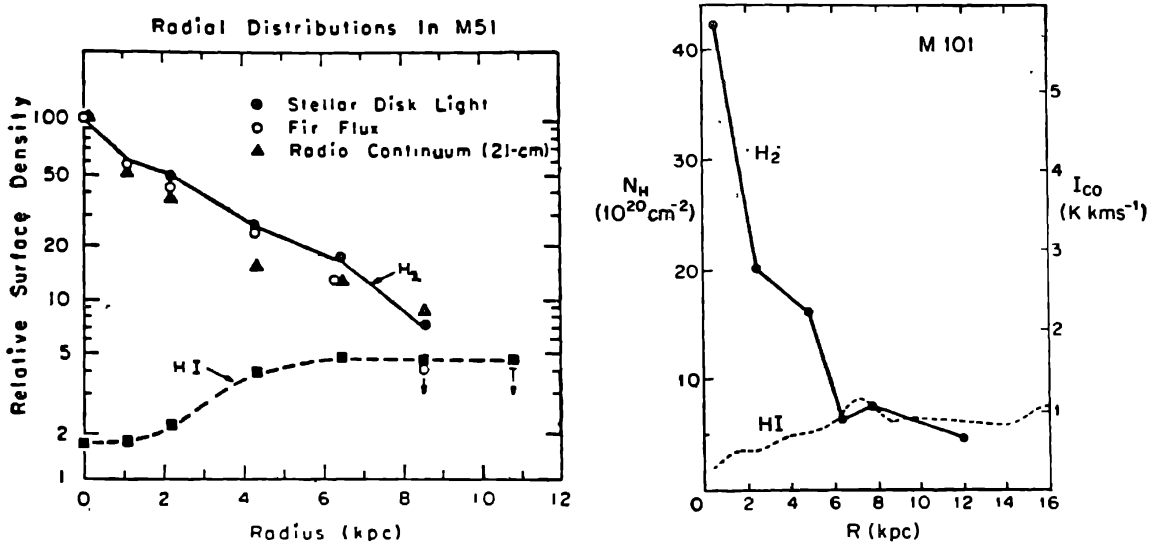


Figure 6. (Left) Comparison of the galactocentric radial distributions of H_2 and $H I$ in M51 from Solomon (1983) who adapted the figure from those of Scoville & Young (1982). (Right) A similar comparison for M101 from Solomon *et al.*

There is some evidence that the total H_2 content and the H_2/HI ratio may systematically increase with later Hubble types (Sa \rightarrow Sc). This, however, has to be considered very tentative at present because it is based on a very small number of galaxies, it is not clear how anomalous M31 might be, and Young & Scoville (1982b) have shown that within a given morphological class (Sc galaxies), the H_2/HI ratios in the central 2.5 kpc varies from ≤ 0.4 in M33 to ~ 32 in M51.

Our galaxy is almost devoid of any interstellar material (HI or H_2) in the radial interval $\sim 1-4$ kpc and has a massive "molecular ring" between 4-8 kpc in which H_2 is the dominant form of the interstellar medium. The CO distributions in the Sc I galaxies so far studied do not have an analogous deficiency at $R = 1-4$ kpc. However Young & Scoville (1982d) find that the two Sb galaxies NGC 7331 and NGC 2841 have bright molecular rings and deficiencies of CO in the inner ~ 2 kpc (*i.e.* molecular holes, see figure 7). Although the case is not as clear, there is some evidence that the edge-on galaxy NGC 1981 (SbI) may also be deficient in CO toward its nucleus (Solomon 1983). Young & Scoville (1982d) claim that the presence of a central hole is related to the presence of significant nuclear bulges and postulate that the interstellar gas originally in these regions may have been used up to form stars in the nuclear bulge. This is obviously controversial and it will require much more observational data before significant progress can be made.

In the last few years it has been found that Magellanic type irregular galaxies have much weaker—in most cases not yet detected—CO emission than Sc type spirals. The irregulars however are well endowed with the constituents that generally accompany

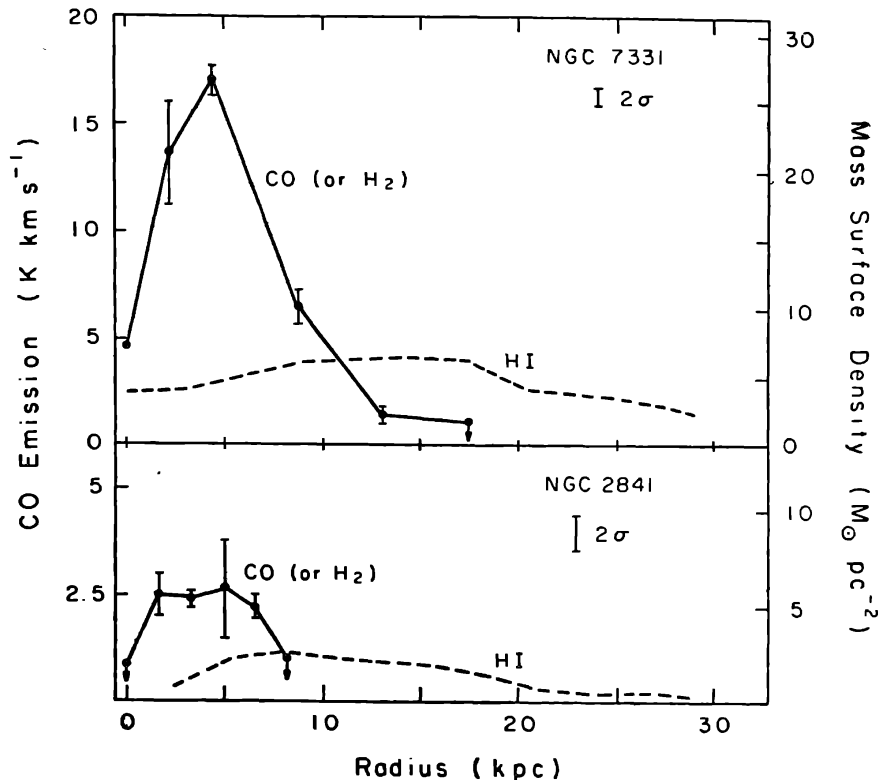


Figure 7. Comparison of the galactocentric radial distributions of molecular (CO) and atomic (HI) mass surface densities in two galaxies (NGC 7331-top and NGC 2841-bottom) believed to be similar to our galaxy in that they have a central hole and a molecular ring (from Young & Scoville 1982d).

large quantities of molecular gas such as bright OB star clusters, H II regions, and dark clouds (as indicated by optical obscuration). It is therefore puzzling why CO emission is so weak (typically a factor of 1/4 or less than that expected if irregulars had the same molecular content as Sc galaxies). See Huggins *et al.* (1975), Elmegreen *et al.* (1980) and Israel *et al.* (1982) for CO observations toward several irregular galaxies. Elmegreen *et al.* (1980) have considered several possible explanations for the anomalous weakness of CO emission from irregular galaxies, but it is clear that this problem still awaits resolution.

There has been considerable controversy over whether galactic molecular clouds are confined to spiral arms. Scoville *et al.* (1979) have claimed that the CO clouds show no evidence for a spiral pattern and many clouds lie in the interarm regions, leading them to conclude that molecular clouds are relatively long lived ($> 10^8$ yr). Cohen *et al.* (1980), on the other hand, concluded that molecular clouds are confined to spiral arms and have lifetimes well below 10^8 yr. Because of systematic noncircular motions (induced by passage through spiral arms, for example) kinematic distances derived from a circular rotation model are highly uncertain. Blitz & Shu (1980), in fact, have claimed that the various galactic CO surveys provide little information on how strongly molecular clouds are confined to spiral arms. Obviously, this is a question which can best be answered by high resolution mapping of CO in a nearby spiral galaxy whose spiral arms can be resolved. Such measurements have been made toward M31 by Boulanger *et al.* (1981) and Stark *et al.* (reported by Linke 1981). Results of these studies show unambiguously that molecular clouds are confined to the spiral arms. Linke (1981) claims that not a single giant molecular cloud lies in the inter-arm region observed by them. The typical limits on arm-interarm CO intensity contrast is $> 4.5:1$ and the peak contrast ratio is $> 12:1$. The position and widths of CO and H I arms (observed with similar resolution) are in good agreement with each other and with the optical spiral arms. As already noted, the molecular to atomic column densities in M31 are low throughout relative to those in the molecular ring in our galaxy and most Sc galaxies; Boulanger *et al.* (1981) found $N(\text{H}_2)/N(\text{H I}) \simeq 0.1-0.2$ in M31, comparable with the *outer* regions ($R > 10$ kpc) of the Milky Way. Thus it is possible that conclusions based on observations of M31 may not be applicable to Sc galaxies (whose $N(\text{H}_2)/N(\text{H I}) \gg 1$ in the central few kpc) and galaxies like ours which has a central hole and a molecular ring where $N(\text{H}_2)/N(\text{H I}) > 10$. Settlement of this question will obviously require more data, particularly for a more typical Sc galaxy.

5. Concluding remarks

In this review I have chosen to discuss only a few topics in some depth rather than attempting to summarize all aspects of interstellar molecules at a superficial level. Even within the areas discussed no claim for completeness is made; a certain amount of selectivity was necessary. I have especially tried to point out some of the areas where major questions remain and to suggest possible next steps. Major areas of research which rely heavily on molecular line studies have either been mentioned only cursorily in relation to other problems or not mentioned at all. It would be wrong for a review of interstellar molecules not to at least enumerate the other research areas in which major efforts are currently being expended. Among these

are obviously the application of molecular spectra as a tool to probe the physical properties of molecular clouds. Much effort has been and continues to be made in the detailed study of star formation processes and the nature of the medium in the immediate neighbourhood of a newly forming star. The study of shell stars via molecular line studies has received much attention in the past few years. In particular, OH (1612 MHz) and SiO maser studies have made major contributions delineating the galactic distribution and nature of oxygen-rich shell stars; carbon-rich shell stars, particularly IRC + 10216, have received some attention from observations of cyanogenated molecules such as CN, HCN, HNC, HC₃N, etc. The relationships between dust and molecular gas continues to be actively studied as is the large scale distribution of molecular clouds within the Milky Way. Pumping mechanisms for the various types of interstellar masers and problems associated with the transfer of their radiation have received considerable attention.

This is certainly not an exhaustive list of research areas involving interstellar molecules, but it should give some idea of the breadth of possibilities this new tool offers to astronomy. With the new Nobeyama 45-metre and the IRAM 30-metre telescopes now coming on line and their associated interferometers not far behind one can certainly expect a new surge of interest and results. With the sensitivity and spatial resolution provided by these instruments one can expect in particular major advances in extragalactic molecular research as well as new insights into the detailed structure of molecular gas in the nucleus of our own galaxy.

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