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Radio Observations of Molecules in the Interstellar Gas [and Discussion]

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Radio observations of molecules in the interstellar gas

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Radio astronomers have succeeded since 1968 in identifying nearly 50 molecules in the dense concentrations of the interstellar gas now generally termed molecular clouds. Most interstellar molecules are stable compounds familiar to the terrestrial chemist, but nearly one-fifth are ions, radicals and acetylenic carbon chains so reactive in the laboratory that before being detected in Space they had rarely been observed or were entirely unknown. The heavy atom backbone of the known interstellar molecules is a linear chain of C, N, O or S (Si is found in two diatomic molecules); rings and branched chains are missing.

The most readily observed spectral lines of most interstellar molecules are rotational transitions at millimetre wavelengths. These are generally excited by H_2 collisions, and depending on the H_2 number density, the levels can be either in rotational equilibrium, or far from it. Maser line emission from OH, H_2O, SiO and CH_3OH – extremely intense, small sources typically much less than 1″ in angular size, often polarized and sometimes time-dependent – are the most striking examples of non-equilibrium excitation.

A number of rare isotopic species are observed in interstellar molecules, those of C, N and O having been studied the most intensively. Isotopic ratios differing from those on Earth by two- or threefold apparently exist, and in all but one case can be attributed to stellar nucleosynthesis since the formation of the Solar System.

Molecular clouds apparently constitute an appreciable fraction of the interstellar medium by mass and are the largest reservoir of matter in Nature subject to the chemical bond. They are of great astronomical interest because of their central role in star formation and galactic structure: it is possible that all stars form in molecular clouds, and as molecular clouds are largely restricted to the spiral arms, they provide a new and highly specific tracer of the large-scale structure of the galactic system.

1. Introduction

Is the chemical bond more than a curiosity from an astronomical standpoint? The possibility of chemistry on a cosmic scale is implicit in one of the earliest and greatest achievements of astronomical spectroscopy: the discovery a century ago that the Sun and stars are composed of the same chemical elements as the Earth; yet as recently as 1968 few molecules had been observed beyond the Solar System, and nearly all were simple diatomic species. Since then, however, radio astronomers working mainly in the millimetre waveband have detected nearly 50 molecules in the interstellar gas, some of remarkable complexity, and with the simpler ones have for the first time succeeded in observing the dense and active condensations of interstellar gas where new stars are formed – objects that have come to be called molecular clouds.

2. ASTROCHEMISTRY

The known interstellar molecules, listed in tables 1–3, consist of 13 simple inorganic compounds, 22 stable organic molecules, and 18 unstable compounds: radicals, ions, isomers and acetylenic carbon chains, both organic and inorganic. The heaviest and most complex interstellar molecule is an unstable molecule of this kind, the carbon chain HC_9N, with 11 atoms and a relative molecular mass of 123 (cf. 10 atoms and a relative molecular mass of 75 for glycine, the simplest amino acid). None of the inorganic molecules in Space contains more than four atoms, so as on Earth it is apparently the carbon bond that is the key to the synthesis of complicated molecules. It is organic chemistry, however, with a particular structural theme: all interstellar molecules have simple linear heavy-atom backbones; branched chains and rings have not been observed.

TABLE 1. INTERSTELLAR INORGANIC MOLECULES

diatomic	*triatomic*	*tetra-atomic*
H_2	H_2O	NH_3
CO	H_2S	
CS	SO_2	
NO	HNO	
NS	OCS	
SiO		
SiS		

TABLE 2. INTERSTELLAR ORGANIC MOLECULES

alcohols		*aldehydes and ketones*		*acids*	
CH_3OH	methanol	H_2CO	formaldehyde	HCN	hydrocyanic
CH_3CH_2OH	ethanol	CH_3CHO	acetaldehyde	HCOOH	formic
		H_2CCO	ketene	HNCO	isocyanic
amides		*esters and ethers*		*sulphur*	
NH_2CHO	formamide	CH_3OCHO	methyl formate	H_2CS	thioformaldehyde
NH_2CN	cyanamide	$(CH_3)_2O$	dimethyl ether	HNCS	isothiocyanic acid
NH_2CH_3	methylamine			CH_3SH	methyl mercaptan
paraffin derivatives		*acetylene derivatives*		*others*	
CH_3CN	methyl cyanide	HCCCN	cyanoacetylene	CH_2NH	methylenimine
CH_3CH_2CN	ethyl cyanide	$HCCCH_3$	methylacetylene	CH_2CHCN	vinyl cyanide

TABLE 3. INTERSTELLAR UNSTABLE MOLECULES

radicals	*ions*		*isomers*	*carbon chains*
CH	CH^+		HNC	HC_5N
CN	$HOCO^+$	⟵ *or* ⟶	HOCN	HC_7N
OH	HN_2^+			HC_9N
SO	HCS^+			
C_2	HCO^+			
HCO				
C_2H				
C_3N				
C_4H				

Interstellar molecules are as a rule composed of only five elements from the first three rows of the periodic table: H, C, N, O and S. The only exceptions are the diatomic silicon compounds SiO and SiS, and these may not be truly interstellar, since they tend to be found in proximity to stars and compact infrared sources. Sulphur compounds are fairly common – eleven have been found – the abundance of these relative to their oxygen analogues generally being close to the cosmic S:O ratio, 1:42; as nearly two dozen interstellar oxygen-containing molecules are known, the detection of more sulphur-containing molecules is presumably only a matter of instrumental sensitivity. Many other elements have been sought as constituents of interstellar molecules but not found, including F, Mg, Al, P, Cl, Ca and Fe.

Owing to the high cosmic abundance of hydrogen, H_2 is by orders of magnitude the most common molecule in the interstellar gas, and in both number density and mass the other molecules rank merely as trace constituents. Far ultraviolet observations of the H_2 Lyman bands (in absorption against distant bright stars) provide direct evidence for this assertion in low- and moderate-density regions; high-density interstellar gas is too opaque in the u.v. (owing to entrapped cosmic dust grains) for observation of the Lyman bands, and the amount of H_2 in such clouds can only be inferred, but the dominance of H_2 has never seriously been questioned. CO, the most abundant radio molecule, has a number density relative to H_2 in dense clouds of about 8×10^{-5}. At the present limit of detection are molecules whose number density relative to H_2 is of the order of 10^{-10}, the limit depending somewhat on the molecule's size and rotational partition function: the large organic molecules in table 2 tend to be hard to see because their partition functions are large and their rotational opacity is spread over many lines. As an example, when corrected for optical depth the HCN:CH_3CH_2CN line ratios in Ori A are about 1000, but the column density ratio is only about 100. The decrease of abundance with size of interstellar molecules, in other words, is not nearly as steep as it appears at first glance, and larger molecules than those in table 2 will probably be found with more sensitive receivers.

As chemical qualitative analysis, the identification of interstellar molecules meets fairly rigorous standards. The spectral lines observed to date are mainly pure rotational transitions at millimetre wavelengths excited by collisional impact with the ambient H_2. Since interstellar molecular gas is often cold and quiescent, line frequencies can be measured very accurately, and can often be matched to laboratory frequencies to a few millionths. A number of lines have been detected for most of the molecules in tables 1–3 (e.g., 20 for methyl formate, 26 for formamide), and most of the interstellar identifications can be considered certain or nearly so. Symmetrical molecules without a dipole moment and allowed rotational spectra cannot as a rule be observed by microwave spectroscopy or radio astronomy, but the existence of several important non-polar molecules can be inferred from the presence of polar derivatives. Thus OCS, CH_3CN and CH_3CH_2CN suggest that CO_2, CH_4 and C_2H_6 (ethane) must be fairly abundant; similarly the presence of the HN_2^+ ion in many sources means that N_2 must be one of the more abundant interstellar diatomics.

Of the 18 unstable molecules in table 3, 10 were discovered in Space before laboratory detection, or are still unknown in the laboratory; their identification has been based on a combination of 'chemical reasoning', quantum chemistry and the detection of fine and hyperfine structure. The two most recently detected such 'non-terrestrial' molecules, HCS^+ and a nearly linear species thought to be either $HOCO^+$ or HOCN, are shown in figures 1 and 2. The identification of HCS^+ has recently been confirmed in the laboratory (Gudeman *et al.* 1981).

Interstellar molecules furnish perhaps the most impressive and interesting examples in astrophysics of non-equilibrium excitation. In very low density clouds the rotational levels of a polar molecule are tightly coupled to an omnipresent thermal reservoir, the 3K cosmic background, and rotational populations will rapidly reach equilibrium at 3K (in about one day). In high-density clouds, however, such a molecule is even more rapidly buffeted by H_2 collisions, and its rotational levels are thereby tightly coupled to a second thermal reservoir, the translational kinetic motion of the molecular gas, characterized for all species by a common temperature T_{kin}. Rotational equilibrium at T_{kin} or quasi-equilibrium between 3 K and T_{kin} is often observed, a good example being the formamide molecule, NH_2CHO, in the distant molecular cloud Sgr B2 (figure 3).

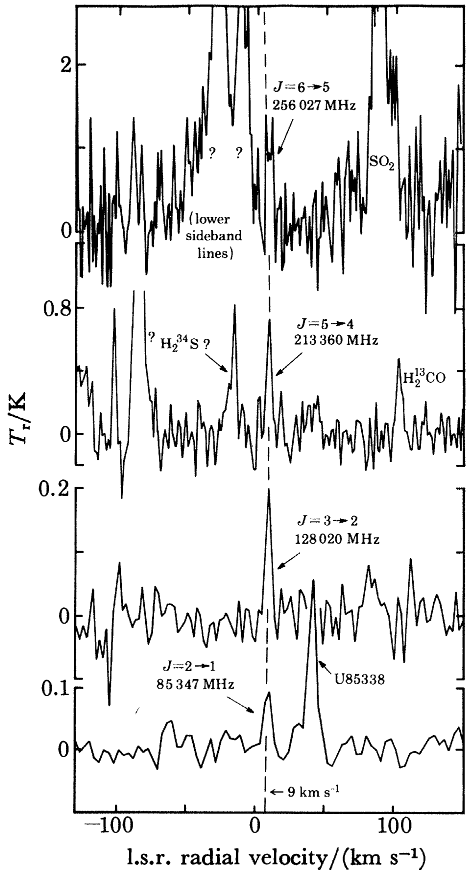

Figure 1. Four harmonically related rotational transitions of HCS^+ in the Orion Nebula (from Thaddeus *et al.* 1981): the first detection of this ion. The rotational constant deduced from these spectra, $B_0 = 21337.15 \pm 0.06$ MHz, agrees closely with that calculated *ab initio* for HCS^+, 21558 ± 216 MHz (Wilson 1978), while the centrifugal distortion constant, $D_0 = 21.4$ kHz, is very close to that measured for the stable isoelectronic system HCP, and this was the basis for the astronomical identification of HCS^+.

At intermediate densities, however, marked departures from equilibrium occur: the molecular levels can be regarded as a thermal engine coupled to hot and cold reservoirs (figure 4), and a detailed knowledge of the collisional and radiative transitions is required to determine level populations. Excitation temperatures [defined from level populations n_i by the Boltzmann relation $n_i/n_j = \exp(-h\nu_{ij}/kT_{\text{ex}})$] greater than T_{kin}, between 3K and T_{kin}, less than 3K, and less than zero (i.e. population inversion), are allowed – and indeed all have been observed for certain molecules under certain conditions. In the vicinity of stars and other infrared sources, coupling to yet a third thermal (or quasithermal) reservoir takes place, and non-equilibrium excitation can exist at high density, where normally it would be collisionally quenched.

A remarkable example of an excitation temperature cooled below 3K is provided by interstellar formaldehyde. Under the impact of H_2 collisions, T_{ex} for the 6 cm lowest-lying transition of the *ortho* levels is reduced to about 2K in many molecular clouds, and line absorption is

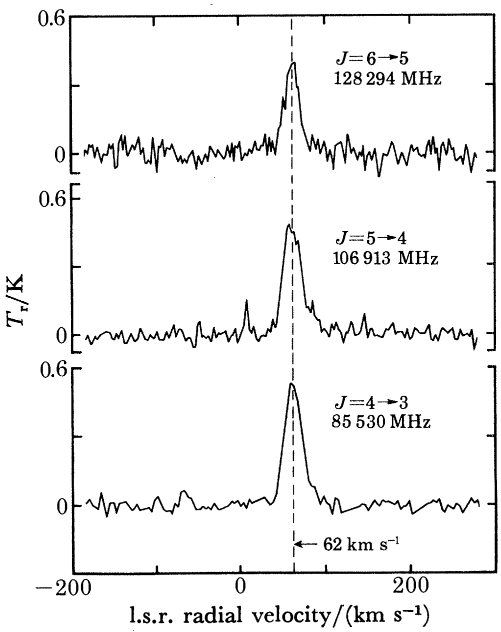

FIGURE 2. Interstellar lines thought to be either the $HOCO^+$ ion (protonated carbon dioxide) or the isoelectronic neutral molecule HOCN (cyanic acid), a terrestrially unstable isomer of the stable compound HNCO (isocyanic acid), an abundant interstellar molecule.

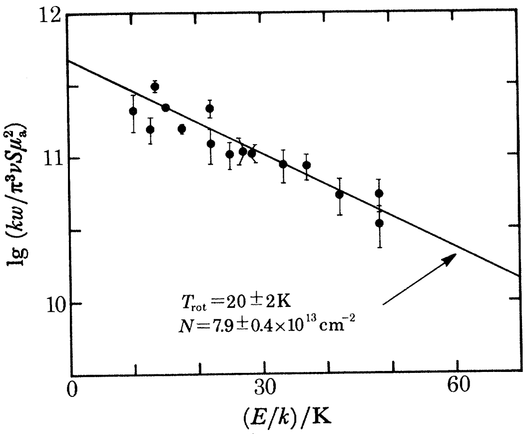

FIGURE 3. Logarithm of intensity plotted against rotational energy for formamide, NH_2CHO, in the molecular cloud Sagittarius B2: an illustration of apparent rotational equilibrium in dense clouds, and a demonstration of the accurate quantitative measurement of molecular column density N now achieved. Data obtained by R. A. Linke with the Bell Laboratories 7 m telescope, analysed by S. E. Cummins.

observed in the absence of any localized continuum source as the isotopic 3K background itself is absorbed by the even 'colder' transition. The perplexity that this effect would have caused had it been observed before the discovery of the microwave background in 1965 can be imagined. Townes & Cheung (1969), on the basis of a semi-classical calculation, first pointed out that H_2 collisions were likely to cool the 6 cm transition in the required way, and their prediction has recently been confirmed by a quantum mechanical calculation of the collisional process (Green *et al.* 1978).

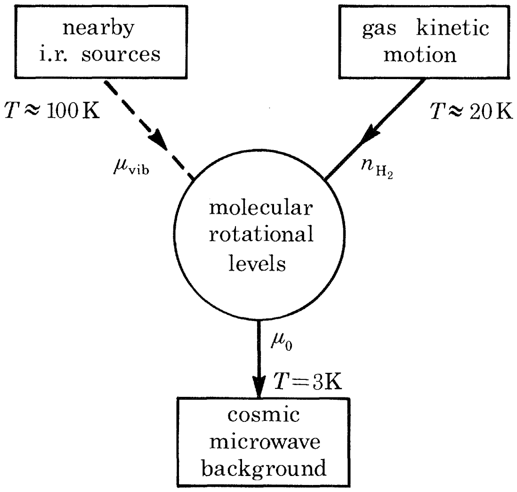

FIGURE 4. Molecular rotational levels in the interstellar gas as a thermal engine.

The most extreme non-equilibrium phenomena are the maser point sources of line emission, observed in one or more transitions of four molecules: OH, H_2O, SiO and CH_3OH (for a current review see Reid & Moran (1981)). Masers are distinguished from normal sources of line emission by one or more of the following properties:

(1) small apparent size (as small as 0.0001″ for H_2O masers);
(2) high brightness temperature (as great as 10^{14} K);
(3) circular or linear polarization;
(4) time variation (sometimes on a scale of a few weeks).

Masers are typically associated with infrared sources and compact H II regions and stars of two types: evolved stars in the process of shedding mass (e.g. Mira variables), and very young stars or protostars still enveloped by the material from which they condensed. The details of the pumping mechanisms which under these apparently quite different conditions maintain population inversion are still unclear after nearly 15 years of study. There is, however, evidence that a combination of infrared and collisional pumping is responsible for many, if not all, masers.

Isotope shifts are generally large in molecular rotational spectra, and since the interstellar lines of many normal isotopic species are saturated, a number of rare isotopic species have been detected (table 4). Isotopic ratios provide in principle unique data on nucleogenesis and the history and the evolution of the Galaxy, and for this reason the rare molecular isotopic species have been intensively studied over the past decade (for a recent review see Penzias (1980)). In deriving isotopic ratios from line intensities, it is generally necessary to correct for both saturation and isotopic fractionation. Fractionation of deuterium is extremely large in certain molecules (*ca.* 10^2 for HCO^+, for example) and for this reason none of the trace molecules of the interstellar gas is well suited for determining the cosmologically important D:H ratio. Fractionation of the C, N and O rare isotopes, however, is much smaller – a factor of 2 or less – and it is possible to correct for it.

Table 4. Interstellar rare isotopes

isotope	terrestrial abundance (%)†	molecules
D		H_2, HCN, HCO^+, HN_2^+, H_2O, H_2CO, NH_3
^{13}C	1.1	CO, CS, HCN, HCO^+, HNC, OCS, H_2CO, HC_3N, CH_3CN, CH_3OH
^{15}N	0.36	HCN, HNC, NH_3
^{17}O	0.04	CO
^{18}O	0.20	CO, OH, H_2CO, HCO^+, H_2O
^{29}Si	4.7	SiO
^{30}Si	3.0	SiO
^{33}S	0.75	CS
^{34}S	4.2	CS, SO, SO_2, OCS

† Relative to normal isotopic species.

In brief outline, the current status of the observational work on isotopic molecules is as follows.

1. Interstellar isotopic ratios, at least of the C, N and O group, seem to be terrestrial to within two- to threefold, and the terrestrial ratios are thus 'universal' to an extent not previously appreciated.

2. There exist, however, distinct differences between certain interstellar and terrestrial ratios. From the Earth and Solar System to molecular clouds in the local spiral arm the ^{13}C:^{12}C and ^{17}O:^{16}O ratios increase by about 30%. and from there to the central region of the galaxy increase a further two- to threefold. These successive increases can be explained by nuclear burning and mass loss by low-mass stars since the formation of the Solar System. The ratio ^{18}O:^{16}O is, however, anomalous: it also increases *ca.* two- to threefold from the local arm to the galactic centre, but the local interstellar ratio is one-half that of the Earth and Solar System. There is currently no good explanation for this decrease.

3. Molecular clouds

Most interstellar molecules have only been observed in a small number of sources, mainly because until quite recently there were few millimetre-wave telescopes equipped with sensitive spectral line receivers. About one dozen of the simpler molecules, however, have been observed throughout the Galaxy, and it is with these that the work on the structure and galactic distribution of molecular clouds has been undertaken. The carbon monoxide molecule CO, specifically its fundamental rotational transition at 2.6 mm, has been by far the most widely used tracer of interstellar molecular gas, and the terms molecular cloud and CO cloud are virtually interchangeable.

There are a number of properties of molecular clouds on which the observers of CO and other simple molecules generally agree, as follows.

1. Though often complex in shape, molecular clouds are as a rule better defined than the clouds of interstellar atomic hydrogen observed with the 21 cm line, and their density contrast

with respect to the ambient gas is probably much higher than that of atomic clouds. Molecular clouds have therefore been generally regarded as discrete *objects* – a separate phase of the interstellar medium – rather than merely local maxima in the density of a turbulent, compressible gas.

2. The largest molecular clouds or cloud complexes are among the largest and most massive objects in the Galaxy, with dimensions of 100–200 pc, and masses as large as 10^6 $M_\odot$. Figure 5, CO maps of two of the largest complexes in the general vicinity of the Sun, gives an idea of the appearance of these impressive objects.

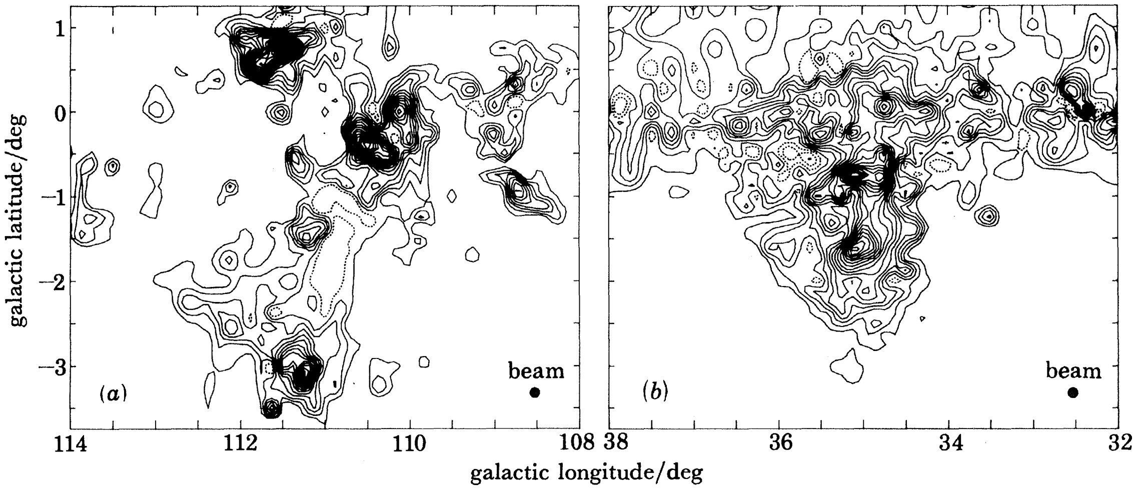

FIGURE 5. Two of the largest and most luminous molecular cloud complexes in the Galaxy: isophotes of integrated CO emission. (*a*) The giant molecular complex associated with NGC 7538 and the supernova remnant Cas A; (*b*) the cloud associated with the supernova remnant W44. (Observations with the Columbia 1.2 m telescope by H. Kong and T. Dame, respectively.)

3. Young OB stars and stellar associations are nearly always found in close proximity to molecular clouds, and often show signs of interacting with them, suggesting strongly that it is from molecular clouds that young stars form. Faint stars like the Sun are inconspicuous at the distance of even the closest clouds (150 pc); it is therefore hard to tell where they form, but the observational data are probably consistent with the general conclusion that *all* star formation occurs in molecular clouds.

4. Molecular clouds constitute a significant fraction of the total mass of the interstellar medium, and are the largest reservoir of 'chemical' matter in Nature.

5. The concentration of molecular clouds in the Galaxy, like that of other young (extreme population I) objects, is greatest at galactocentric distances between 4 and 7 kpc.

6. The total CO luminosity of the galaxy is dominated by the largest molecular clouds or complexes of the kind shown in figure 5.

The exact mass of molecular clouds, individually and *in toto*, how they are distributed in the Galaxy, where they form and how long they live, and whether or not they are gravitationally bound, are more controversial issues. Consider first the question of mass.

It is the radio astronomers' recourse to trace constituents in studying molecular clouds that is the root of the difficulty in determining mass. There is evidence and general agreement that CO is a good qualitative tracer of H_2, but the constancy of the CO:H_2 ratio even in the local arm has not been demonstrated to within a factor of 2 or 3, and has not been determined at all in the distant inner arms of the Galaxy where most molecular clouds are found. There the CO:H_2 ratio may be systematically higher than that locally, as the atomic C:H and O:H ratios increase toward the centre in some spiral galaxies. Hence the total galactic mass of molecular clouds obtained from the CO luminosity:mass is not much better than an order of magnitude estimate. In the distant inner Galaxy the molecular and atomic components of the interstellar medium may be roughly equal by mass, or either may be dominant by as much as three- to fivefold.

Knowledge of the galactic distribution of molecular clouds is of fundamental importance in

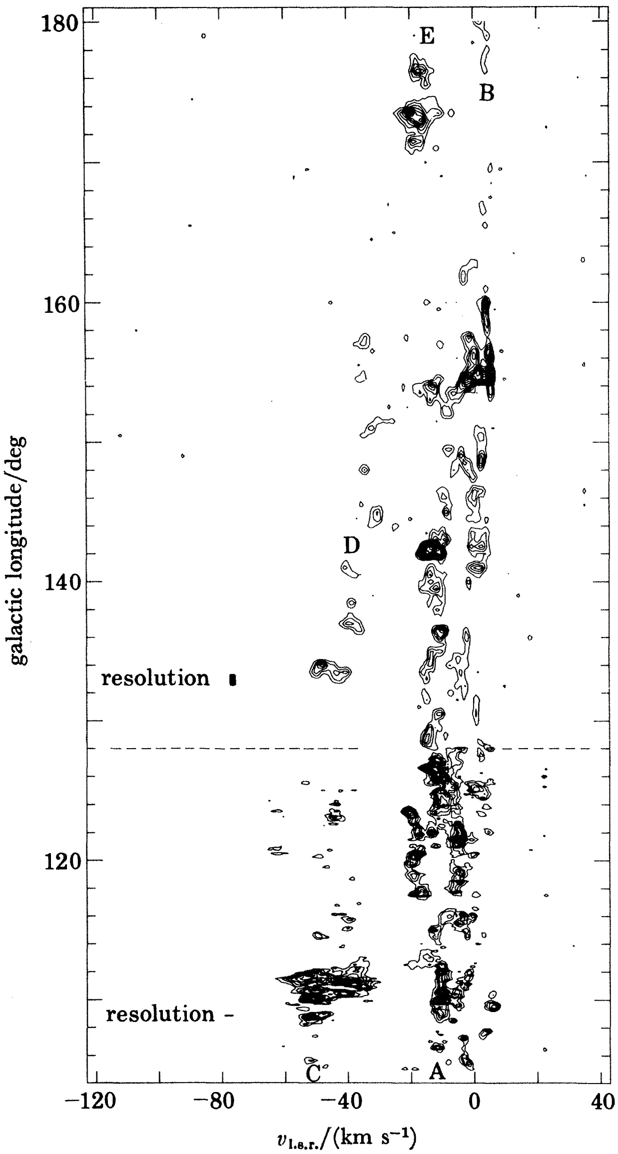

FIGURE 6. Longitude–radial velocity diagram of molecular clouds in the second galactic quadrant, obtained with the Columbia 4 ft (*ca.* 1.3 m) telescope. The intense vertical lane of clouds at $v_{l.s.r.} = -20$ to $0\ \mathrm{km\ s^{-1}}$ is the local arm; the fainter curved lane at -60 to -40 $\mathrm{arcsec^{-1}}$ is the Perseus arm (from Cohen *et al.* 1980).

determining how and where they form, how long they live, and their total mass relative to the rest of interstellar gas. When the intimate connection between molecular clouds and stellar associations and H II regions – the classical optical tracers of spiral structure – was established in the mid-1970s, many radio astronomers expected that CO would prove a better tracer than the 21 cm line of the large-scale spiral structure of the Galaxy. The first two systematic CO surveys of the galactic plane gave at best ambiguous support to this expectation, one providing evidence for a 'higher-order arrangement' of molecular clouds, which might indicate regular arms (Burton & Gordon 1978), the other finding molecular clouds both in the putative 21 cm arms and in the interarm regions as well, the arm – interarm contrast being fairly small (Scoville *et al.* 1979). Both surveys indicated that the most prominent molecular structure in the Galaxy is an annular concentration of molecular clouds between 4 and 7 kpc from the galactic centre – larger than any of the postulated spiral arms in this region – which became known as the 'molecular ring'. Scoville *et al.* (1979) took the low arm–interarm contrast to mean that molecular clouds are old objects, with lifetimes as long as 1 Ga, and asserted '. . . we must abandon the notion that the molecular clouds represent a brief compression phase through which the interstellar medium passes each time a galactic shock passes by'.

Several recent CO surveys, however, contradict this conclusion. They indicate that the arm–interarm contrast in the distribution of molecular clouds is actually fairly large, and was originally overlooked simply because the first surveys were severely undersampled, or were largely confined to the first galactic quadrant. One of these, a closely sampled CO survey of the second quadrant done with a 1.2 m telescope at Columbia University, is shown in figure 6: a standard longitude–velocity map of CO isophotes obtained by numerically integrating across the 6° strip in galactic latitude covered by the survey. Between the local arm AB near zero radial velocity and the curving Perseus arm CDE at negative velocity is a conspicuous lane 20 km s^{-1} wide almost entirely free of molecular clouds that can be followed for at least 40° in longitude. Many of the molecular clouds in figure 6 are related to stellar associations and H II regions at known distances, and hence a good estimate of the dimensions of this interarm region can be made: it is 1 kpc wide and at least 3 kpc long. Within this large region the number density of molecular clouds in projection on the galactic plane is at most one-fifth that in the adjacent Local and Perseus arms.

The existence of this gap – and the fairly well-defined character of the Perseus arm beyond – is an important clue to the nature of molecular clouds, implying that they are formed as gas enters a spiral arm, and are largely dissipated before it leaves. An upper limit to the age of a cloud is the time required for a parcel of interstellar gas to cross an arm, which at 10–13 kpc from the galactic centre is unlikely to be longer than 100 Ma (making allowance for possible density wave perturbations tending to maintain the trajectory within the arm). The actual lifetime may be considerably shorter than this limit, as there is evidence that local stellar associations and galactic clusters dissipate the molecular gas from which they formed in 30 Ma or less (Bash *et al.* 1977). Also, the molecular mass of the Perseus arm deduced from the survey data in figure 6 (and ^{13}CO observations) is fairly low, being only a small percentage of the interstellar atomic (H I) mass. Thus, at least in the solar neighbourhood, fairly definite conclusions on the nature of molecular clouds can be reached: they are essentially transient objects, and are not the dominant mass fraction of the interstellar gas.

A second CO survey done with the Columbia telescope, in the first galactic quadrant and summarized in figure 7, suggests that these conclusions also hold in the molecular ring. One of the most important findings of this survey is the hole E in figure 7 near the middle of the ring, which in longitude–velocity space is roughly the intense trapezoidal band of emission ABCD. The existence of this hole is not in dispute; it has now been confirmed by Solomon and co-workers with the N.R.A.O. 36 ft (*ca.* 11 m) telescope, and at higher sensitivity by Stark with the Bell 7 m telescope, who finds an arm–interarm contrast of at least 10:1. In radial velocity the width of this hole equals or exceeds that of the interarm gap in figure 6 towards the Perseus arm, and it too must represent an empty region several kiloparsecs in length, though it extends only 4° in longitude, for we are viewing the arms in this direction nearly end-on. Thus E is probably an interarm region comparable with that observed towards the Perseus arm, and by the same reasoning as before, it implies that in the molecular ring – as locally – molecular clouds are essentially transient objects.

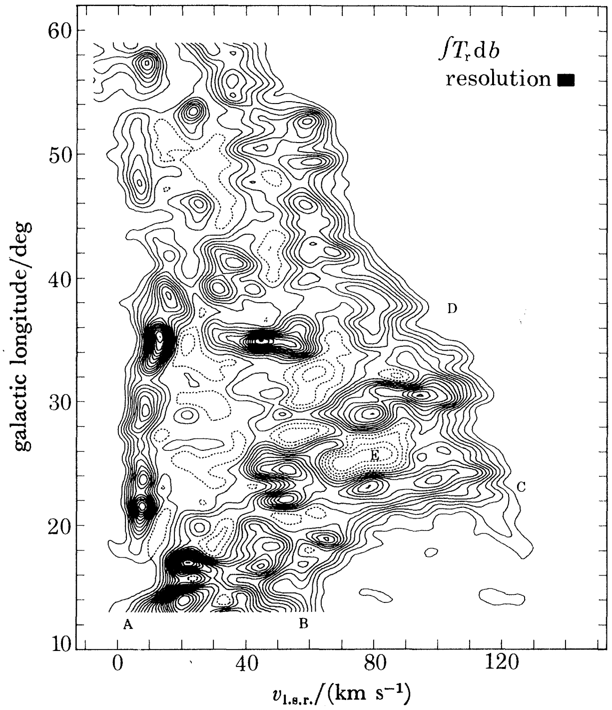

FIGURE 7. Longitude–radial velocity diagram of molecular clouds in the inner Galaxy: the Columbia CO survey of the first galactic quadrant, numerically integrated in galactic latitude over the 2° strip centred on the equatorial plane covered by the survey, and smoothed by 1° in longitude and 5 km s^{-1} in radial velocity. Broken contours represent holes in the CO emission.

It has been said that trying to understand the Galaxy from observations only from the Northern Hemisphere is like a bird trying to fly with one wing (Eddington 1930). Carbon monoxide surveys of the southern Milky Way are just starting in Australia and Chile, and with luck should settle the question of the galactic distribution of molecular clouds and their relation to spiral structure. The main task ahead in galactic structure studies is of course to *improve* our knowledge of the large-scale structure of the Milky Way, but in the controversy over the nature of molecular clouds this has largely been neglected or deferred.

In this brief review it has been impossible to do justice to many areas of observational research in the very active field of interstellar molecules. Observations with CO of molecular clouds in other galaxies, which began slowly owing to limitations on receiver sensitivity, are now advancing (Stark 1979), and should accelerate greatly when large single-element antennae and interferometers now under construction are completed. The important study of molecules in circumstellar shells and other compact objects is a second topic of research that stands to benefit from the new instrumentation.

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Discussion

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CO *emission and spiral arms in the inner Galaxy*

Over the past few years we (D. Sanders, N. Scoville and myself) have carried out an extensive survey of CO emission from the inner galactic plane in order to study galactic structure and the physical properties of molecular clouds, and to determine the total mass of molecular clouds in the Galaxy. Our conclusions differ in many important ways from those of the survey discussed by P. Thaddeus although the 'picture' of CO emission in longitude–velocity space is very similar. The difference is primarily one of interpretation and not of sampling, surveying methods or telescope size.

The motivation for this survey of the inner Galaxy was provided by our earlier finding that on a galactic scale the CO emission and giant molecular clouds were concentrated in a 'ring' inside the Sun ($R_0 = 10$ kpc) between $R = 4$ and 8 kpc (Scoville & Solomon 1975) from the centre of the Galaxy, a distribution that is strikingly different from the flat radial distribution of atomic hydrogen. We interpreted this CO emission, supplemented by a few ^{13}CO spectra, as indicating that within the ring the mass in molecular hydrogen clouds substantially exceeded the H I mass. A similar conclusion was reached the following year by Gordon & Burton (1976). The molecular ring appeared to be an important feature of galactic structure, a region of the Galaxy with strong population I, where the ratio of mass in hydrogen molecules (dense clouds) to mass in atoms was about five times higher than at the solar circle.

Our current survey consists of two main sets of data. The first is ^{12}CO observations at $\lambda = 2.6$ mm every 1° longitude and every 0.2° latitude from $l = 0°$ to $l = 70°$, with a total of 1300 spectra. The second consists of observations every 2′ (4′ between 40° and 50°) in longitude (following the latitude of maximum emission) along the plane from $l = 10°$ to $l = 52°$. This second data set contains about 1100 observations with the 36 ft (*ca.* 11 m) antenna of N.R.A.O.

which has a half-power beamwidth of 1.1′; this beamwidth corresponds to a size of 2.5 pc in the molecular ring at a distance of 8 kpc or 5 pc between successive observations. This is much smaller than the size of clouds that emit most of the CO radiation.

A moderate size cloud in the ring, 30 pc in length, will be sampled in six successive observations. Thus the use of a large antenna and small beamwidth allows individual clouds to be mapped simultaneously with a determination of their galactic distribution. This high-resolution survey is taken at a much higher frequency than the separation between objects; individual objects or clouds are resolved. Thus features on a scale from 20 pc to several kiloparsecs can be

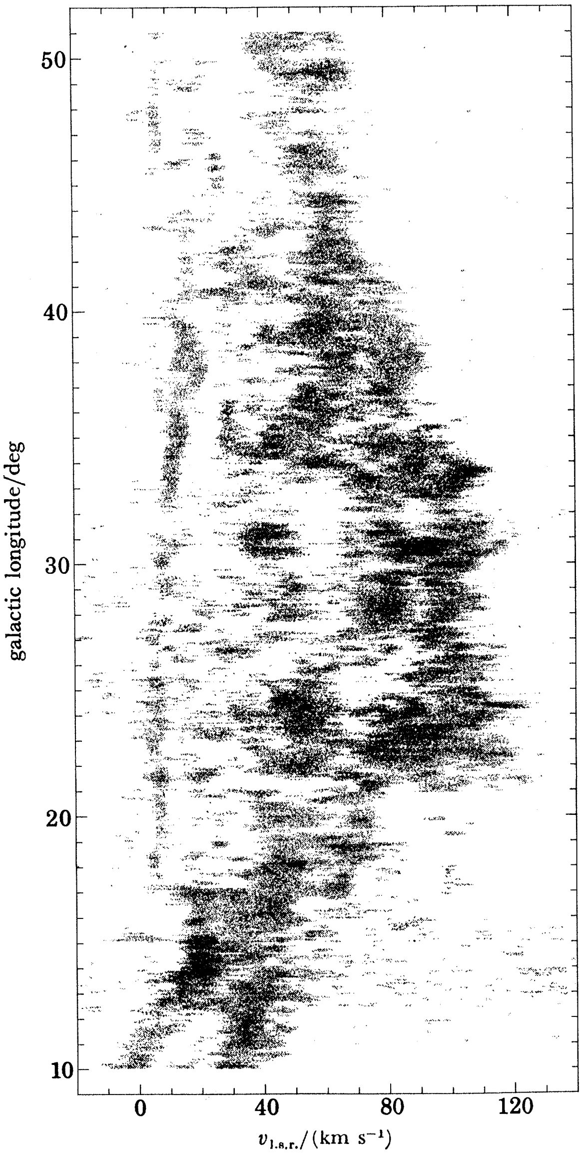

FIGURE d1. CO emission in longitude–velocity space. Data set includes about 1000 spectra spaced every 0.03° in longitude (18° < l < 40°) and 0.06° in longitude (10° < l < 18° and l > 40°). The latitude of the observations follows the maximum emission in the galactic plane primarily at b = 0.0 and b = −0.2 except below longitude 18°. The number of dots is linearly proportional to the CO antenna temperature, with velocity resolution of 2 km s^{-1}. Saturation is at $T_a^* > 12$K. No dots are plotted for $T_a^* < 1$K (see text). (See Sanders *et al.* (1981) for a more complete discussion.)

traced. Our preliminary analysis of some of these data indicated that most of the mass in the i.s.m. in the interior of the galaxy was in giant molecular clouds with individual masses greater than $10^5 M_\odot$ (Solomon *et al.* 1979; Solomon & Sanders 1980).

Pictures of CO *emission in longitude–velocity space and spiral structure*

In the longitude–velocity diagram (figure d1) all of the high-resolution data are plotted with the density of points linearly proportional to the CO emission line strength. The dynamic range of the CO emission intensity on this picture is a factor of 12 with saturation for $T_a^* > 12$K and no dots for $T_a^* < 1$K. Some of the largest giant molecular cloud complexes associated with well-known strong H II regions (e.g. M17 at l = 14–16°, v = 20 km s^{-1}; W43 at l = 30.7°, v = 90 km s^{-1}, W44 at l = 34–36°, v = 50 km s^{-1}, W51 at l = 49.5°, v = 55 km s^{-1}) are easily discernible. We have analysed these data to determine the reality of putative spiral arms and determine the contrast along the terminal velocity region where distances may be assigned without the double-value problem. Some general characteristics of the emission are described below.

Contrast in l–v space

There is very high contrast between structures a few degrees in length and empty regions. Thus inspection of the diagram shows contrasts as high as a factor of 12, and factors of 5 are quite common. The empty region or holes at l = 28–33°, v = 50–70 km s^{-1}, and l = 24.5–27°, v = 65–85 km s^{-1}, have less than 10 % of the emission of the strongest cloud complexes and less than 20 % of the emission of regions of comparable size. This is much higher than any observed contrast in H I. The point of disagreement with the spiral arm interpretation given by Thaddeus is on the question of whether or not this contrast can be traced over many tens of degrees and corresponds to self-consistent patterns due to spiral arms. It is the existence of well-defined galactic-scale spiral arm patterns, not the existence of giant complexes with high contrast, that bears on the astrophysical question of whether or not clouds form and exist only in spiral arms.

In order to have a quantitative measure of contrast in/out of putative spiral arm patterns we have determined the CO emissivity along the terminal velocity ridge from l = 21° to l = 52°. This samples emission along paths 3 kpc long at galactic radii from 3.6 to 7.8 kpc along the line of sight at the point nearest to the galactic centre. Spiral arms tangential to the line of sight will appear as emission peaks 2–4° wide. Spaces between spiral arms should appear with no or very little emission if they are empty of molecular clouds. Figure d2 shows that the entire ridge is filled with substantial emission with five peaks superimposed. Collectively the peaks occupy 30 % of the effective area in the projected plane and contain 50 % of the emission. This picture is clearly not consistent with a model that locates all of the molecular clouds in only two or three arms in the inner Galaxy. The emission between l = 37° and l = 42° near the maximum velocity, which would be empty in the schematic of the Galaxy drawn by Thaddeus (see Cohen *et al.* 1980), actually has more emission than the putative Sagittarius arm.

Large-scale loops in l–v space and spiral arms

The gross characteristics of CO longitude–velocity space are very similar to H I. On this point there is no disagreement. Indeed we have previously noted that 'the two major spiral features deduced from 21 cm line observations of the northern hemisphere are the Scutum and Sagittarius arms, tangential to the line of sight at longitudes of 33° and 50° with radial velocities

100 and 60 km s^{-1}; concentrations of CO emission corresponding to the tangential direction of these two arms are clearly seen . . . in CO emission neither of these features can be traced over more than 10° in longitude' (Scoville *et al.* 1979). However, we concluded that 'most of the clouds cannot be situated in a regular spiral pattern'.

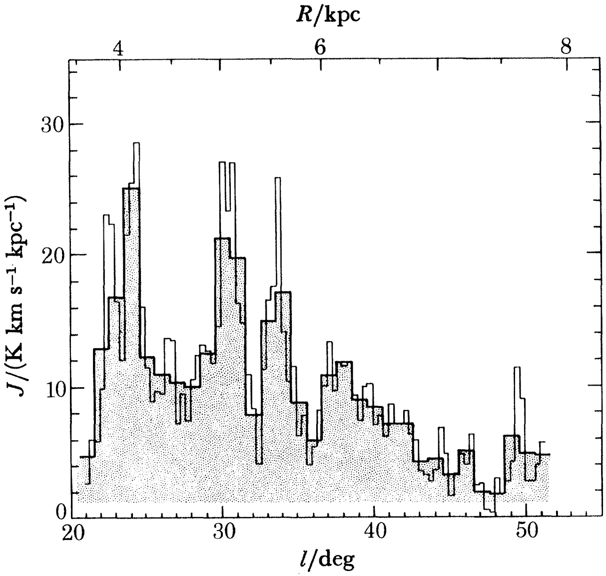

FIGURE d2. CO emissivity along the tangent point as a function of longitude. Data are binned at $\Delta l = 0.33°$ representing 10 scans and 1.0° representing 30 scans. Emission is observed at all locations with five peaks superimposed. If all molecular clouds were confined to the spiral arms there would be no emissivity in this picture between $l = 35°$ and $l = 48°$.

TABLE d1. DISTANCES TO MOLECULAR CLOUDS AND H II REGIONS ON THE 'FAR SIDE' OF THE 'SAGITTARIUS SPIRAL ARM' IN *l–v* SPACE

object	l/deg	v/(km s^{-1})	distance/kpc	note
molecular	30	43	far, 13	1
H II	34.2	53	near, 4	2
molecular	34–36	40–60	near, 4	1
H II	35.2	46	near, 3	2
H II	35.6	52	near, 4	2
	37.6	55	far, 12	2
molecular	37	52	far, 12	1
molecular	43	60	(near, 5)	1
H II	45.4	55	near, 4	2
H II	46.5	55	near, 4	2

Notes: (1) Determined from latitude size in this CO survey and scale height determination.
(2) Determined by Lockman (1979) from H II region absorption lines.

Thaddeus (this volume and in Cohen *et al.* 1980) concludes that in the inner Galaxy, molecular clouds are completely confined to the regular spiral arm pattern indicated by loops in longitude–velocity space found by 21 cm observers. The longest spiral arm feature that appears in the face-on picture of the Galaxy presented by Thaddeus is in the 'Sagittarius arm', which supposedly contains all the CO emitting molecular clouds between 6 and 9 kpc from the

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galactic centre at longitudes between 20° and 52°. This is deduced on the basis of an apparent loop pattern in longitude-velocity space that is most prominent as a continuous band of emission between longitudes 33° and 50° in figure 8 (see also the l–v diagram of Thaddeus). The strongest apparent continuity of this loop is at velocities from 50 to 65 km s^{-1} corresponding to the far side of the 'spiral arm'. We find that this continuity of emission in longitude–velocity space is actually due to a mixture of clouds at distances (from the Sun) varying between 4 and 12 kpc although separated in longitude by only a few degrees. If this band of emission at v = 50 km s^{-1} were a real arm, all of the features would be at the far-side kinematic distance.

In table d1 we present a brief summary of the mixture of cloud distances that make up the 'far side' of this loop. The distances were determined either by use of scale height information from our CO survey (large angular scale height yielding a near kinematic distance) or from H II region data in the literature where distances are assigned on the basis of absorption line velocities (Lockman 1979). The continuity at v = 50 km s^{-1} between longitude 30° and 50° is clearly not a physical spiral arm but a superposition of sources at widely ranging distances. Combined with the absence of strong emission at the tangent point of this putative spiral arm we find no evidence for the Sagittarius spiral arm over this large section of the Galaxy.

Of course there may well be a region corresponding to the Sagittarius direction near M17 at lower longitudes where there is a real concentration of clouds, but no consistent 'arm' exists containing all of the clouds between 6 and 9 kpc.

Total mass of molecular clouds in the 4–8 kpc *ring and ratio to* H I

On the basis of this ^{12}CO survey and ^{13}CO data (Solomon *et al.* 1979) we have determined the total mass and distribution of H_2 in the inner Galaxy. Using the abundance ratio $^{13}CO:H_2 = 10^{-6}$ we find a total H_2 mass in dense clouds between 4 and 8 kpc of $2.2 \times 10^9 M_\odot$. This compares with $0.4 \times 10^9 M_\odot$ for H I yielding $M(H_2)/M(H\,I) = 5.5$ in the ring (83 % molecular). The above ^{13}CO abundance corresponds to 15 % of available ^{13}C in CO and is in good agreement with a recent dark cloud measurement by Ferking *et al.* (1981). If we adopt Dickman's (1978) earlier finding of 2×10^{-6}, or 30 % of available ^{13}C in CO, we still find the majority of the i.s.m. in molecular clouds within the ring with $M(H_2)/M(H) = 2.75$, or 73 % molecular clouds. To reduce the estimated molecular fraction significantly below 50 % would require more than 100 % of available ^{13}C in ^{13}CO or a very large correction to H I mass. The two possible corrections to the H_2 mass, galactic abundance gradients (which actually enter only as the square root of the abundance due to the nonlinear curve of growth), and non-l.t.e. effects, both a maximum of a factor of 2, will work in opposite directions leaving the fraction of the i.s.m. in the ring, which is molecular in the range 73–85 %. From continuity arguments this large a percentage of total i.s.m. cannot be strictly confined to a spiral arm pattern.

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P. Thaddeus. A brief comment on Solomon's table 5: most of the objects listed as 'near' – specifically the objects in rows 2–5 inclusive – are part of the molecular complex associated with the supernova remnant W44 shown in my figure 5. This is one of the largest molecular complexes in the Galaxy, with internal velocities spaced over nearly 40 km s^{-1}. It is little wonder that kinematic distances assigned to portions of this complex make little sense. If these objects are set aside, the remaining objects in table 1 say very little about the presence or absence of the Sagittarius arm.

W. L. H. Shuter (*Department of Physics, University of British Columbia, Vancouver, Canada*). The longitude–velocity diagrams for CO showing details of galactic structure presented by Dr Thaddeus and by Dr Solomon are referred to the conventional local standard of rest (l.s.r.). I should like to caution against the use of this for studying the kinematics of the galactic disc on a large scale, and suggest that a 'rotational standard of rest' differing by about 9 km s^{-1} from the l.s.r. might be more appropriate. This is particularly important in attempting to unravel 'spiral arms' because an incorrect choice of the standard of rest can distort a circular feature centred on the galactic centre into a two-armed spiral.

A. W. Wolfendale, F.R.S. (*Physics Department, University of Durham, U.K.*). The role of cosmic rays in heating the i.s.m. and in generating ions, which in turn cause molecular reactions to proceed, has been mentioned. Here, attention is devoted to the production of γ-rays by the interaction of cosmic rays with the gas in dense molecular clouds.

Issa & Wolfendale (1981) have recently examined the published data from the SAS II and COS B γ-ray satellites and made estimates of the γ-ray fluxes from a number of local molecular clouds. The masses of these clouds, derived largely from the estimates of the Thaddeus group (Blitz 1980), have been used to estimate the γ-ray fluxes expected if the intensity of cosmic ray particles in the clouds were the same as near the Earth (after correcting for solar modulation). Division of the observed γ-ray flux by that expected gives the factor F by which the cosmic ray flux in the cloud is enhanced over the local value. Figure d3 gives values of F for the clouds examined in this way.

Inspection of figure d3 shows that for clouds within about 2 kpc of the Earth the median value of F is close to unity. In so far as it is very likely that the cosmic ray intensity is roughly constant over this region, the implication is that the Blitz mass estimates are probably correct; in turn, the conversion $N(H_2)/N(^{13}CO) \approx 4 \times 10^5$ receives some measure of confirmation (although in fact we increased the derived mass by 50 % to allow for various phenomena).

Beyond 2 kpc there appear to be cases where F is significantly greater than unity. These may represent examples of clouds containing sources of cosmic ray particles, they may be clouds whose masses have been underestimated, or they may be in regions where the ambient cosmic ray intensity is significantly higher than locally.

In conclusion, a plea is made for more precise estimates of the masses of local molecular clouds so that the argument can be used in its preferred form, namely to use the γ-ray fluxes from known clouds to chart the magnitude of the cosmic ray intensity in the Galaxy.

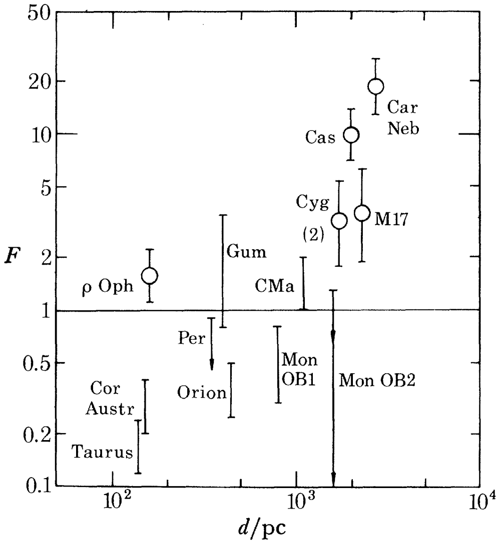

Figure d3. Ratio (F) of cosmic ray intensity in molecular cloud to local intensity as derived from determination of γ-ray flux due to cosmic ray interactions with the gas in the clouds. The F values are plotted against the distance of the cloud from the Earth; the results beyond 1–2 kpc are increasingly uncertain. Ringed circles indicate clouds that are probably identified with 'sources' in the 2CG catalogue (COS B) of Swanenburg *et al.* (1981). There are two 'sources' in the Cygnus region.

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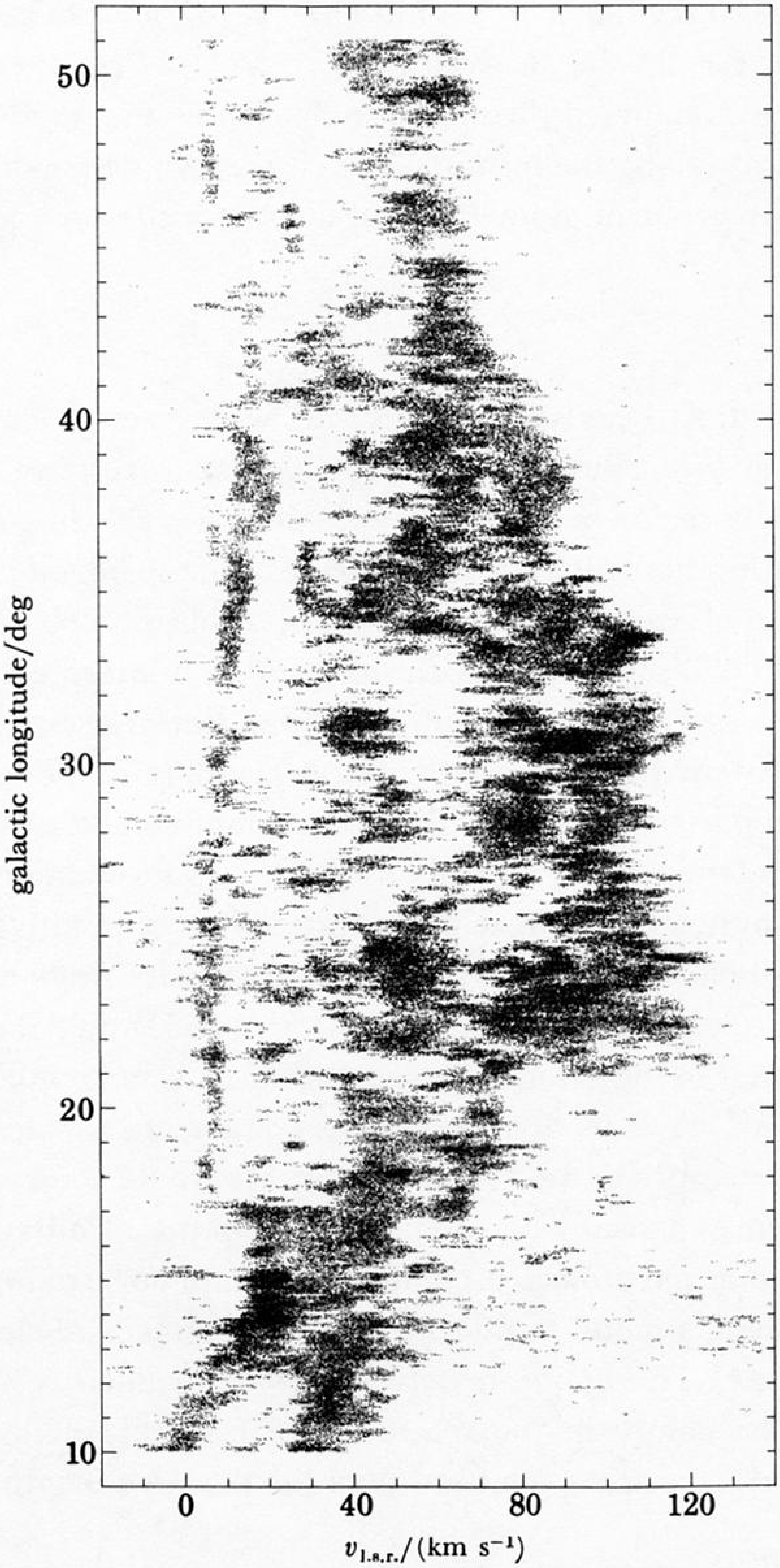

FIGURE d1. CO emission in longitude–velocity space. Data set includes about 1000 spectra spaced every 0.03° in longitude ($18° < l < 40°$) and 0.06° in longitude ($10° < l < 18°$ and $l > 40°$). The latitude of the observations follows the maximum emission in the galactic plane primarily at $b = 0.0$ and $b = -0.2$ except below longitude 18°. The number of dots is linearly proportional to the CO antenna temperature, with velocity resolution of 2 km s^{-1}. Saturation is at $T_a^* > 12$K. No dots are plotted for $T_a^* < 1$K (see text). (See Sanders *et al.* (1981) for a more complete discussion.)