STATISTICAL MODELING OF CO EMISSION IN THE GALAXY

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We summarize here some of the distribution properties of CO clouds in our galaxy as determined by observation and by computer simulations of these observations. The simulations adequately account for the number of clouds, their spatial separation, and their relative velocities with respect to one another. The principal shortcoming of the axisymmetric simulations is their failure to describe adequately the clustering of clouds seen in the velocity-longitude domain.

The 2.6-mm emission line of carbon monoxide has been extensively used to explore the optically inaccessible regions of the galactic plane. The first major survey, by Wilson et al. in 1974, dealt primarily with known discrete sources of continuum radio emission. Subsequent surveys, listed as references for Table 1, deal with the general morphology of the cold interstellar gas irrespective of the discrete sources.

Although by themselves the CO spectra give information about the distribution of cold material in the galaxy, the construction of computer simulations give additional insight. The Monte Carlo procedure which we have followed involves construction of a model of the CO distribution within the galactic disk, "observation" of this model by means of a simulated telescope, and subsequent comparison graphically and quantitatively of features found in the observed and modeled data. The initial constraints to the model are those determined unambiguously from the observations. Iterative trial and error guided changes in the simulation.

Specific results on the distribution characteristics of CO clouds

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CHARACTERISTICS OF CO IN THE GALAXY

Property	Value	Source	Reference
Kinematics	like HI	Terminal velocities	2,7
Galactic radial extent	$4 < \varpi < 10$ kpc	Longitude extent, kinematic distances	1,2,3,6,7
Abundance maximum	$\varpi = 5.7$ kpc	Longitude extent, kinematic distances	1,2,3,6,7
<z extent>	h = 50 pc, $n(z) = \exp(-z^2/2h^2)$	Latitude extent, kinematic distances	4,6
Mean layer	like HI	Latitude extent, kinematic distances	4,6,9
Uniformity of distribution	heavily clumped	Velocity-longitude diagram	1,2,7
<Cloud separation>	1 kpc, increasing away from $\varpi = 5.7$ kpc	Computer simulation	2,7
Cloud - cloud velocity	$\sigma = 4$ km s^{-1}	Computer simulation	2,7
Number of clouds	$< 10^6$	Computer simulation	2,7
Cloud occultation	barely unimportant	Computer simulation	2,7
Cloud density within layer	$< 5 \times 10^{-5}$ pc^{-3}	Computer simulation	7
Fractional volume of layer	< 0.3%	Computer simulation	7
Total mass of CO	$> 10^6$ $M_\odot$	Computer simulation	3,7
Cloud diameters	Most between 5 and 30 pc	Observation	7,8
Cloud masses	3×10^4 to 10^6 $M_\odot$	Virial theorem	1,7,8
Internal turbulence	$\sigma = 2.5$ km s^{-1}	Terminal velocities, isolated clouds	2,7
Cloud lifetimes	$> 2 \times 10^7$ y	Computer simulation	5

1 Scoville and Solomon 1975
2 Burton e- al. 1975
3 Gordon and Burton 1976
4 Burton and Gordon 1976
5 Bash et al. 1977
6 Cohen and Thaddeus 1977
7 Burton and Gordon 1978
8 Gordon and Burton 1978
9 Lockman 1977

in the galaxy are summarized in the table. Initial results on the galactic morphology of clouds were based on observations made with an uncooled receiver by Scoville and Solomon (1975) and by Burton, Gordon, Bania, and Lockman (1975). Subsequent papers by various authors generally are based on improved observations made with a cryogenic receiver. In our series of papers, Paper I (ref. 3 in the table) deals with the distribution of cold interstellar gas as a function of galactocentric radius. Paper II (ref. 4) deals with observations and simulation of the latitude extent of the CO layer. Paper III (ref. 7) summarizes results from a rather extensive survey and its computer simulation. Related papers include one on the sizes of molecular clouds (ref. 8) and one on the determination of the pattern speed of the density wave in our galaxy (Gordon, 1978). An attempt has been made by Roberts and Burton (1977) to incorporate the precepts of the density-wave theory in the Monte Carlo simulations. A parallel effort at incorporating these precepts into computer simulation of CO observations has been made by Bash, Green, and Peters (1977). In both attempts, the CO clouds behave as ballistic objects after passing through the galactic density wave. The Bash *et al.* approach results in a determination of a cloud lifetime.

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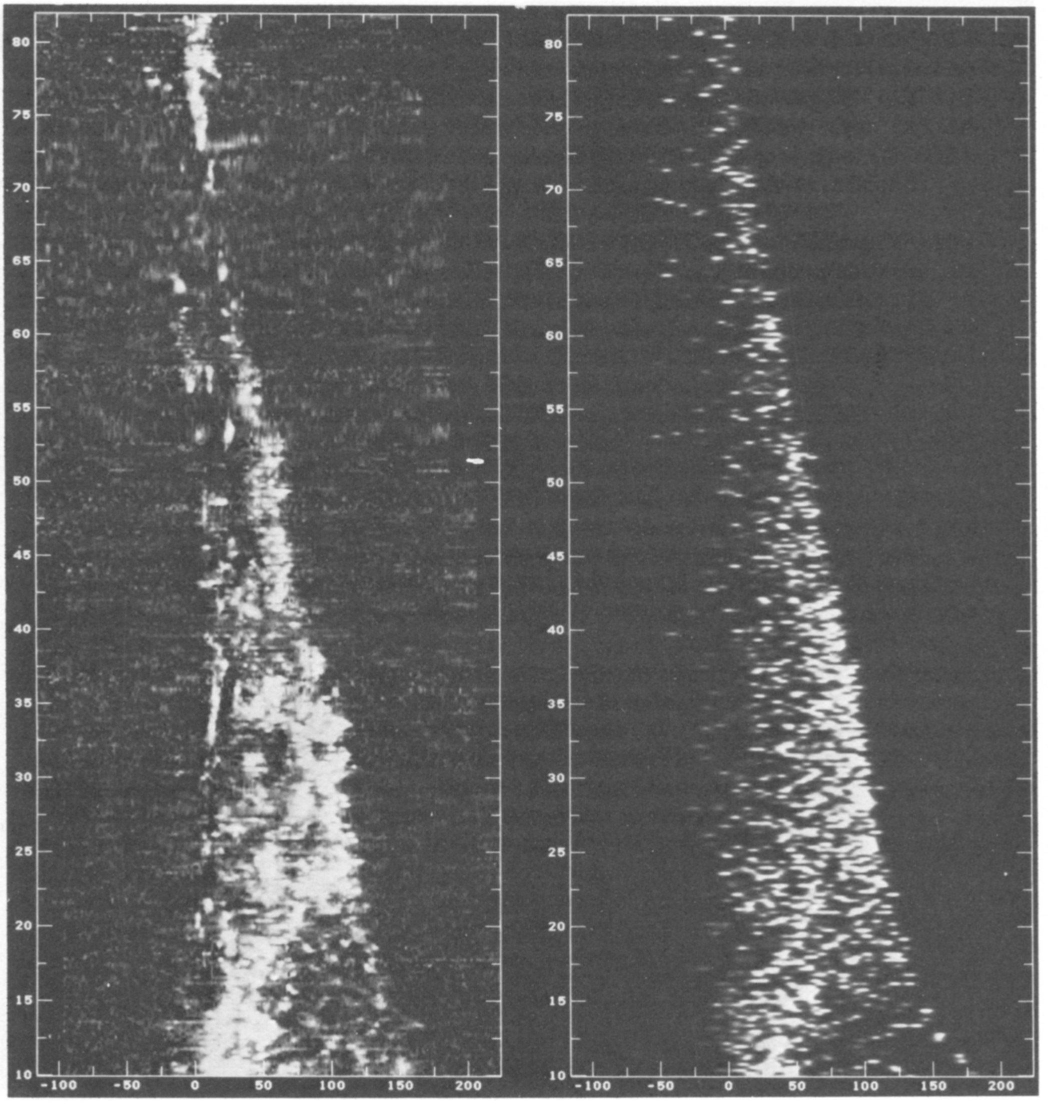

Figure 1. (left) Grey-scale representation of the longitude-velocity arrangement of ^{12}CO emission observed at 0°2 intervals along the galactic equator. (right) Longitude-velocity arrangement of emission inherent in synthetic spectra representing stochastically distributed discrete CO clouds (Burton and Gordon, 1978).

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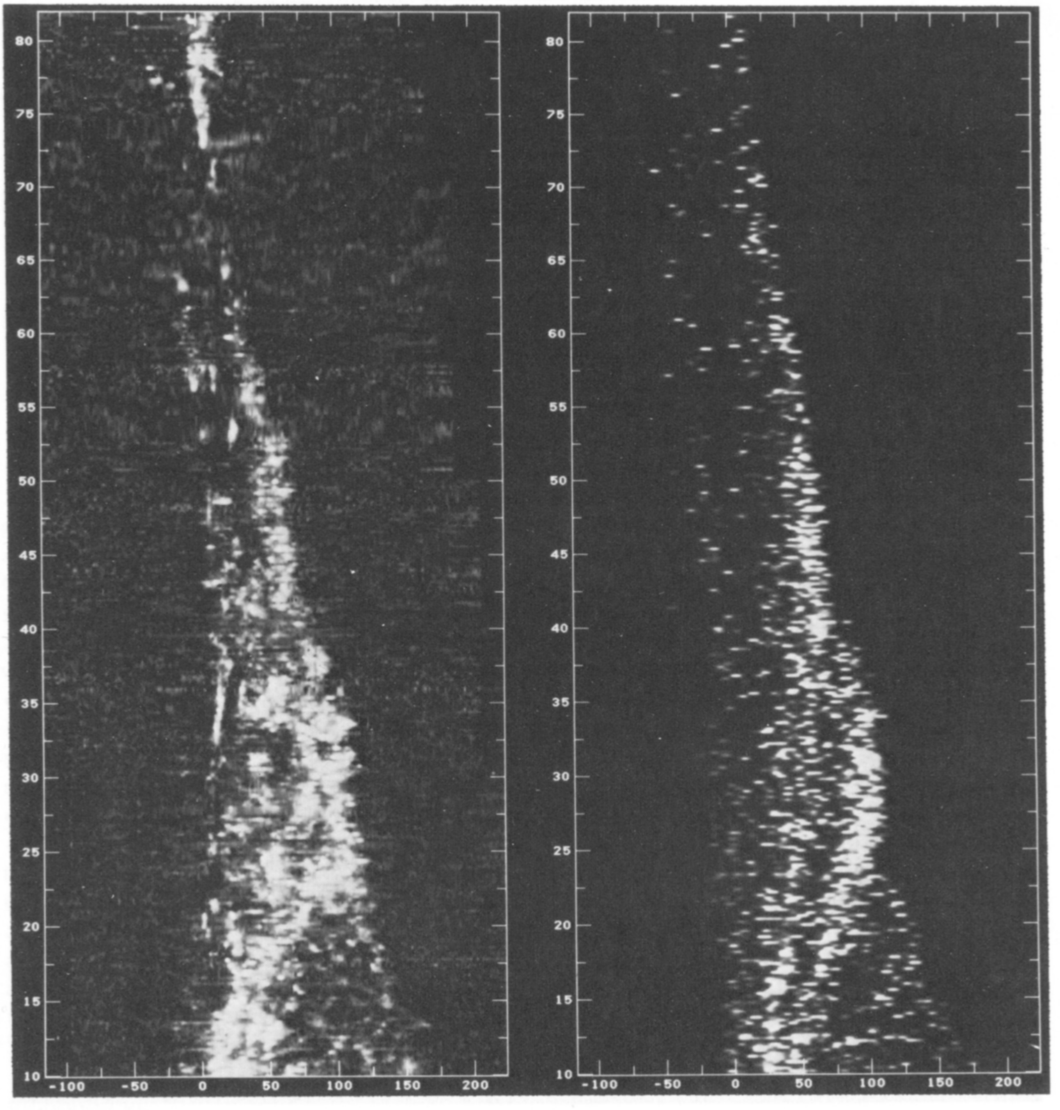

Figure 2. Comparison of the longitude-velocity arrangement of ^{12}CO emission observed at b=0° with the situation representing CO distributed stochastically in discrete clouds in a spiral model. The clouds' kinematics and probability of occurrence follow the predictions of the density-wave theory (Roberts and Burton 1977).

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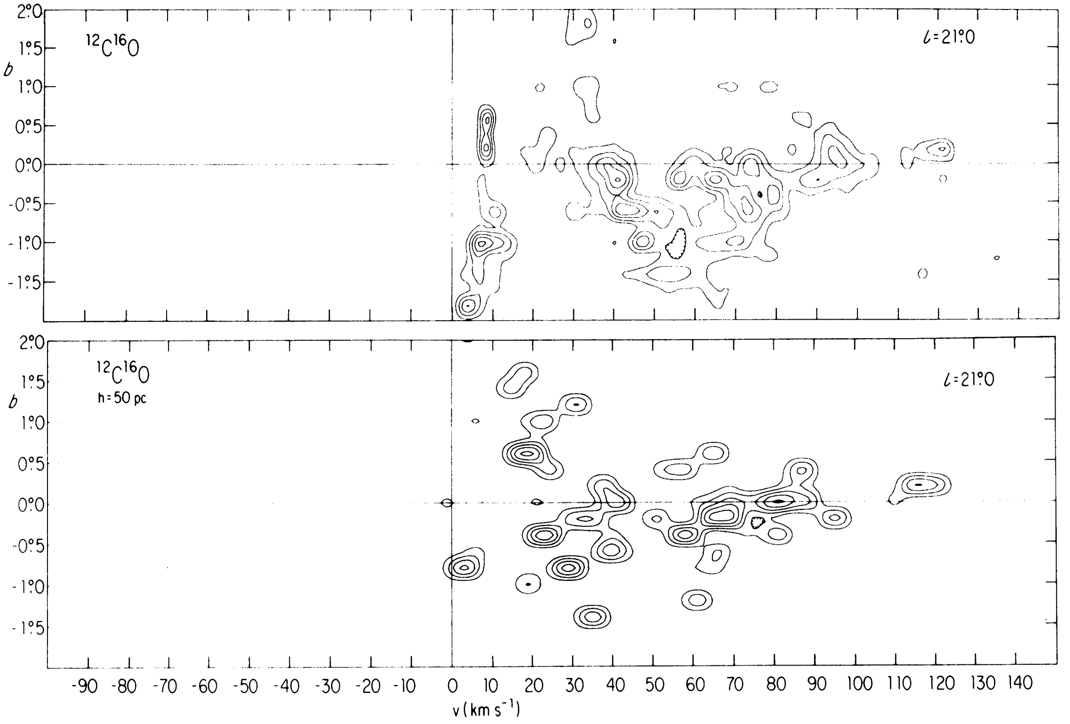

Figure 3. (top) Observed latitude-velocity distribution of CO emission in the direction $\ell=21°$. (bottom) Computer simulation of this CO layer. The scale height in the form $n(z)=\exp(-z^2/2h^2)$ is 50 pc in this simulation.

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DISCUSSION

Sinha: What is your definition of the outer boundary of the CO distribution? Chi Yuan described his detection of a substantial number of CO clouds in Perseus; others have observed CO clouds to farther distances in the anticenter direction.

Burton: The CO abundance distribution continues to fall off gradually at ϖ > 8 or 10 kpc. The accumulated emission which remains is much less than at smaller distances. The CO surveys have until recently been principally confined to b = 0°. If the CO layer were to be strongly warped, some emission would remain undetected, and the outer-region abundances would need revision. However, there is sufficient data at b ≠ 0° to indicate that this effect is not substantial.

Shuter: What value do you use for the random velocities of the clouds? I suggest that you check the consistency of this with the new determinations of scale height because the scale height and random velocities are simply related.

Burton: The one-dimensional dispersion is 4 km s^{-1}, a value derived principally from the scatter in the terminal velocities. We have not made the check you suggest.

van den Bergh: Photographs of external galaxies show that the densest dusty regions have a vein-like structure. Is there any evidence to indicate that galactic CO clouds also have such a structure?

Burton: The sampling interval of the CO data is still too coarse to provide an answer to this.

Bash: Regarding the lifetime of CO-emitting molecular clouds, I would just like to make the point that one can fill the CO v,ℓ diagram, similar to the way it is observed to be filled, by assuming that molecular clouds are launched from the spiral shock wave and live 3×10^7 years.

Burton: The cloud-cloud velocity dispersion, which is measured in one dimension to be 4 km s^{-1}, is not large enough to fill the v,ℓ space if the starting distribution is a simple pattern. (Unfortunately, we do not know much at all about the underlying fundamental pattern.)