THE BELL LABORATORIES $^{13}$CO SURVEY: LONGITUDE-VELOCITY MAPS

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ABSTRACT

A survey is presented of the Galactic plane in the $J = 1\rightarrow 0$ transition of $^{13}$CO. About 73,000 spectra were obtained with the 7 m telescope at Bell Laboratories over a 10 yr period. The coverage of the survey is $(l, b) = (-5^\circ$ to $117^\circ$, $-1^\circ$ to $1^\circ$), or 244 deg$^2$, with a grid spacing of $3\arcmin$ for $|b| < 0.5$ and a grid spacing of $6\arcmin$ for $|b| > 0.5$. The data presented here have been resampled onto a $3\arcmin$ grid. For 0.68 km s$^{-1}$ channels, the rms noise level of the survey is 0.1 K on the $T^*_B$ scale. The raw data have been transformed into FITS format, and all the reduction processes, such as correcting for emission in the reference positions, baseline removal, and interpolation, were conducted within IRAF using the FCRAO task package and additional programs. The reduced data are presented here in the form of longitude-velocity color maps at each latitude. These data allow identification and classification of molecular clouds with masses in excess of $\sim 10^3 M_\odot$ throughout the first quadrant of the Galaxy. Spiral structure is manifested by the locations of the largest and brightest molecular clouds.

Subject headings: Galaxy: structure — ISM: clouds — ISM: molecules — surveys

1. INTRODUCTION

Surveys of carbon monoxide (CO) emission lines are the primary means for gathering information about the distribution and kinematics of molecular material in the Galaxy. The observer, when embarking on a CO survey, must choose the survey parameters with an eye to the astrophysical problem to be attacked because millimeter-wave telescopes have limitations in observing speed, sensitivity, and resolution. Rapid improvements in technology have allowed ever larger and more finely detailed surveys, but the current state of the art is not yet able to produce detailed, low-noise maps of every molecular cloud in the Milky Way. Combes (1991) has reviewed 16 CO surveys and discussed the results. Early surveys, such as Schwartz, Wilson, & Epstein (1973), Burton & Gordon (1978), and Solomon, Sanders, & Scoville (1979), determined the large-scale distribution of CO in the Milky Way. The Columbia Mini and Southern Mini surveys (Dame et al. 1987; Bronfman et al. 1988), in particular, measured the CO emissivity of the whole Galaxy and determined its distribution on scales larger than $\sim 50$ pc. Later surveys have concentrated on molecular cloud properties and the relationship between molecular clouds and Galactic structure. The Bell Laboratories $^{13}$CO survey presented here was designed to identify most of the molecular clouds in the first quadrant of the Galaxy and provide some information about their size, shape, and velocity. It differs from previous surveys in the accuracy with which clouds can be identified and the molecular line emissivity parceled out among them. These data will be used to approach the problem of spiral structure and its effect on molecular clouds and star formation.

Several statistical studies (Scoville et al. 1987; Solomon et al. 1987; Sodroski 1991) of the giant molecular clouds (GMCs) identified in survey data have led to significant results on the kinematics of disk structure, locations and extent of spiral arms, and the mass and size spectra of the GMCs. These analyses were based on a simple methodology for recognizing molecular clouds in survey data. In these studies, a molecular cloud is defined as a region in $(l, b, v)$ survey space where the $^{12}$CO line emission exceeds a particular threshold brightness temperature. The tendency for $^{12}$CO lines from different clouds to blend together because of spatial and velocity crowding and optical depth effects has led to the choice of a high value for that threshold. Scientifically important inaccuracies in our quantitative understanding of the distribution of molecular gas may result, especially in crowded regions, such as the molecular ring. Small clouds may be missed entirely because even their central brightnesses may not exceed the threshold, while large clouds are sometimes spurious blends of objects at different distances. Significant crowding of molecular material occurs throughout the first and fourth quadrants of the Galaxy, especially on the locus of tangent points. Along any line of sight toward the inner Galaxy, the point on the line closest to the Galactic Center is the tangent point, and clouds near this point have the largest velocity and the most velocity crowding. Clouds at the tangent point are, however, particularly interesting because they are at an inflection point in the velocity-distance relation and therefore have unambiguously determined distances.

The $^{12}$CO line becomes optically thick toward most molecular clouds. The isotopically substituted $^{13}$CO molecule is a more accurate tracer of molecular column density, because its optical depth is a factor of $\sim 50$ times smaller than that of $^{12}$CO. Data obtained in the $^{13}$CO (1–0) emission line with a large spatial coverage and a high resolution can be used to quantitatively study the molecular material near young stellar objects, since the more optically thin emission traces dense regions where star formation takes place. While the $^{13}$CO lines are several times weaker than $^{12}$CO, its smaller opacity, relatively high abundance ($^{13}$CO/H$_2 \sim 10^{-6}$ in the solar neighborhood; Frerking, Langer, & Wilson 1982), and the relatively greater transparency of the atmosphere at 110 GHz make $^{13}$CO the species of choice for surveying molecular gas in crowded regions. Surveys conducted in $^{13}$CO can be used to separate and catalog clouds better than $^{12}$CO surveys.
The primary disadvantage of $^{13}\text{CO}$ surveys is that they are less sensitive to weak CO emission than are $^{12}\text{CO}$ surveys. Weak $^{12}\text{CO}$ emission has been detected in small interstellar clouds (see, e.g., Magnani, Blitz, & Mundy 1985) and in a thick molecular layer associated with the whole Galactic disk (Dame & Thaddeus 1994). Such material has a $^{13}\text{CO}/^{12}\text{CO}$ line intensity ratio that is smaller than that of most molecular material, and the $^{13}\text{CO}$ emission is therefore more likely to be buried in noise. The low noise level of the present survey partially compensates for this effect. In the region covered by the present survey, essentially all clouds seen in $^{12}\text{CO}$ surveys are also seen here.

Several $^{13}\text{CO}$ surveys were completed in the 1980s (Liszt, Burton, & Xiang 1984; Jacq, Baudry, & Walmsley 1988; Bronnman et al. 1989). These are, however, all one-dimensional—limited to the Galactic midplane ($b = 0$). Aside from the Bell Laboratories $^{13}\text{CO}$ survey, systematic two-dimensional $^{13}\text{CO}$ surveys of the Galactic plane have been conducted only toward limited regions: Nagoya University’s $^{13}\text{CO}$ map made with their 4 m telescope (27 beamwidth) with a spatial sampling of 8' toward the Cygnus region (Dobashi et al. 1994), Taurus (Mizuno et al. 1995), the Cepheus and Cassiopeia region (Yonekura et al. 1997), and most recently, the antiGalactic center region (Kawamura et al. 1998). There are plans to survey the whole Galactic plane with the two Nagoya 4 m telescopes (Nagoya University in Japan and Las Campanas Observatory in Chile), and a significant portion has been completed (Tachihara et al. 1997).

In this paper, we present the results of a $^{13}\text{CO}$ survey covering a third of the Galactic plane at a spatial sampling of 3' using the 7 m telescope at Bell Laboratories. The Bell Laboratories $^{13}\text{CO}$ survey was designed to detect and distinguish molecular clouds in the first quadrant larger than about $10^3 M_\odot$. The survey has enough resolution to locate star-forming regions within large clouds. It does not, however, provide much detail of the internal structure of the clouds. The large longitude coverage allows the study of GMCs in a Galactic context, while the sampling grid size allows some indication of their internal structure. In § 2 is a description of the survey parameters and statistics, telescope and receiver systems, observing techniques, and reduction procedure. In § 3, the data are shown as longitude-velocity color maps, one at each latitude, and the principal characteristics of the survey data are discussed.

2. THE SURVEY

2.1. Telescope and Receiver System

The data were obtained with the 7 m off-axis Cassegrain radio telescope located at Bell Laboratories, Crawford Hill in Holmdel, New Jersey (Chu et al. 1978) between 1978 and 1992. The beamwidth (FWHM) of the telescope is 103' at the frequency of the $^{13}\text{CO}$ $J = 1-0$ line (110.20913 GHz). A Schottky diode receiver system developed by R. A. Linke was used for the early data; after 1982, Superconductor-Insulator-Superconductor mixer receivers developed by R. A. Linke and A. A. Stark were used. The superconducting junctions were fabricated by R. E. Miller and A. A. Stark at Bell Laboratories, Murray Hill. Single-sideband (SSB) operation was achieved using a Fabry-Pérot filter in reflection that had an 11–15 dB rejection of the image sideband. The unwanted image sideband transmitted through the Fabry-Pérot filter was terminated in a millimeter-wave load with a 28 K radiation temperature. The receiver was located at a nontilting Nasmyth focus in a housing located on the azimuth structure. The receiver was calibrated by chopping between an ambient temperature load and a liquid nitrogen-cooled load located near the Cassegrain focus. The single-sideband receiver temperature of the receiver systems ranged from 76 to 360 K during the years of observation, with typical values around 120 K. The atmospheric sky brightness was measured several times each hour by chopping between the 77 K Cassegrain cold load and the sky. The correction for atmospheric opacity was then calculated using a plane-parallel atmospheric model. Typical SSB atmosphere-corrected system temperatures were $T^* \sim 600$ K. Observations were not made when $T^*_s$ exceeded 1000 K. The 7 m antenna has a main beam efficiency of 89% at 100 GHz; another 5% of the detected power comes from the antenna sidelobes, and about 6% comes from the ground pickup. The spectra were obtained with a 256 channel filter bank consisting of filters with a 250 kHz spacing and a 512 channel filter bank consisting of filters with a 1 MHz spacing. The individual filters in these filter banks have rectangular bandpasses with little overlap between adjacent filters. The frequency domain is therefore slightly undersampled.

2.2. Spatial Coverage and Sampling

The range of the survey is $(l, b) = (-5^\circ$ to $117^\circ, -1^\circ$ to $1^\circ)$, comprising about 244 deg$^2$. Table 1 lists the regions observed and the data sampling within those regions. In Figure 1, the grid spacing and beam size of the Bell Laboratories $^{13}\text{CO}$ survey is compared with those of other surveys: the Columbia $^{12}\text{CO}$ Galactic plane survey and University of Massachusetts-Stony Brook $^{13}\text{CO}$ first quadrant Galactic plane survey (UMass-SB) are shown in thick solid-line circles, and the Nagoya University $^{13}\text{CO}$ and Bell

![Fig. 1.—Beam sizes and spatial sampling grids of major CO Galactic plane surveys. The $^{13}\text{CO}$ surveys of UMass-SB (beam size 45') and Columbia (8.7) are represented as thin solid-line circles, and the $^{13}\text{CO}$ surveys of Nagoya University (170') and Bell Laboratories (103') are represented as thick solid-line circles on a 3' grid.](image-url)
Laboratories $^{13}$CO surveys are represented in thick solid-line circles on the 3' grid. A total of 73,000 positions were observed.

2.3. Observations

All observations are position-switched data. Each spectrum is a weighted average of observations at its “on” position and two “off” positions. The Galactic center data are described by Bally et al. (1987). The data with $|l| > 5^\circ$ were obtained with a multiple map position switching technique. This means that during the data acquisition, observations of five on positions were temporally interspersed with observations of two off positions, and the spectra from all five on positions were used exactly same off measurements. Each of the two off positions were observed for $\sqrt{2}/2$ times longer than the individual on positions in order to optimize the noise level and observing speed. The multiple-map technique increases the speed of the observations but has the undesirable effect that the noise in the five resulting spectra is somewhat correlated: the on data for each position (including associated noise) are unique, but the off data (including associated noise) are the same for all five spectra. The five on positions are separated by 0.2°, so positions with correlated noise have three other grid points with totally different noise between them.

The Galactic coordinates of each set of five points are given by

$$\begin{align*}
  l_{\text{on}} &= L + 0.2M + \Delta l, \\
  b_{\text{on}} &= \Delta b,
\end{align*}$$

where $0^\circ \leq \Delta l < 0.2^\circ$, $-1^\circ \leq \Delta b \leq 1^\circ$ in 0.05 increments, $M$ varies from 0 to 4 during the course of a single multiple map position switch, and $L$ varies from 10° to 117° in 1° increments during the course of a day's observations. $\Delta l$ and $\Delta b$ were fixed for each day's observations. The Galactic coordinates of the reference positions are given by

$$\begin{align*}
  l_{\text{off}} &= L + 0.5, \\
  b_{\text{off}} &= \pm 3^\circ.
\end{align*}$$

There are, therefore, only 216 off positions in the survey. These off positions are not necessarily free of emission. The method by which the spectra were corrected for emission in the off or reference position is described in § 2.4.

The typical on-source integration time was 8.3 s for each of the five on positions and 9.3 s for each of the two off positions, for a total position switch cycle of 60 s. This minute-long cycle was repeated 6–40 times (depending on the opacity of the sky) so that the rms noise in each spectrum after calibration is 0.1 K in 250 kHz channels. In good weather, it was possible to complete a full set of observed points having particular values of $\Delta l$ and $\Delta b$ (that is, all the points with $M$ and $L$ ranging over their full set of allowed values) in one day. In poor weather, the Galactic plane would set before a full set of points could be obtained, and the undone points would be rescheduled for a later day.

Receiver calibration was accomplished by chopping between an ambient temperature load and a load filled with boiling liquid nitrogen. Sky brightness measurements were accomplished by chopping between the liquid nitrogen load and the sky. These measurements were made at roughly 20 minute intervals. All antenna temperatures quoted here are corrected for atmospheric extinction and for the forward spillover and scattering losses of the antenna ($\eta_{\text{ls}} = 0.91$) and are therefore on the $T_B$ brightness temperature scale as defined by Kutner & Ulich (1981). In order to convert to a $T_{mb}$ brightness temperature scale, the data as presented here should be multiplied by 1.02 ± 0.02.

These data were obtained during hundreds of days of observing over the 10 yr period. Observations were made by A. A. Stark, R. W. Wilson, J. Bally, M. Pound, G. R. Knapp, and W. D. Langer. Some results of this survey have been presented by Stark (1979, 1983), Stark, Penzias, & Beckman (1983), Stark et al. (1987, 1988), and Bally et al. (1987, 1988). Advances in computation and the recent availability of powerful data reduction and display packages now permit the full data set to be rereduced and presented here.

2.4. Data Reduction

The raw OBS format spectra were calibrated and a linear fit to the baseline was removed in the Bell Laboratories data reduction program COMB. The resulting COMB stacks were written out as three-dimensional ($v$, $l$, $b$), FITS format data cubes, which can be manipulated with the standard data reduction packages IRAF and AIPS. For the region $l > 5^\circ$, the COMB stacks data were written onto a (partially filled) 3' grid in ($l$, $b$) and a 0.68 km s$^{-1}$ (one filter-bank channel width) grid in velocity. The size of the data cube outside the Galactic center region is ($v$, $l$, $b$) = (364, 2241, 41) pixels. Unfilled positions on the 3' grid were filled in by linear interpolation over the nearest four positions using IRAF and SAOimage. We used the FCRAO task package and developed scripts within IRAF to interpolate and reduce the data. A second-order baseline fit was subtracted from the spectra. Bad channels caused by the malfunction of individual filters in the filter bank were identified in the FITS image and fixed by interpolating adjacent good data over the bad pixels.
As described above, the off positions used for the position switch are not necessarily clean of emission. About 2% of the raw spectra were contaminated with negative features resulting from emission in the reference positions. Essentially all this emission is within the velocity range \(-5\) to \(5\) \(\text{km s}^{-1}\) and almost certainly originates in dark clouds near the Sun. The strongest of these features was less than 0.5 K. Since each off position was used for several hundred on positions at the same value of \(L\), it is likely that at least one on position is free of emission at the velocity at which the off is contaminated. The on position spectra sharing the same \(L\) were therefore searched for the biggest negative feature. Data in a small range of velocities around this biggest negative feature were extracted from that spectrum. These extracted data were then taken to represent the emission in the off position, and it was subtracted from all the on positions sharing the same value of \(L\). About 0.03% of the pixels were modified by this method. A comparison with the UMass-SB \(^{12}\text{CO}\) database shows that these recovered pixels do not show a systematically different ratio of \(^{12}\text{CO}\) to \(^{13}\text{CO}\).

After removing the effects of the contaminating emissions in the off positions, the database was combined with the Galactic center survey FITS data cube (Bally et al. 1987). The Galactic center data were interpolated into a 3' grid and a 1 \(\text{km s}^{-1}\) grid. Thus, the final database including the Galactic center region is \((v, l, b) = (501, 2441, 41)\) in pixel units, and the velocity range is \(-250\) to \(250\) \(\text{km s}^{-1}\), longitude is \(-5^\circ\) to \(117^\circ\), and latitude is \(-1^\circ\) to \(1^\circ\).

### 2.5. Survey Brightness Statistics

A histogram of the number of \(l\), \(b\), and \(v\) data points versus the brightness temperature of the \(^{13}\text{CO}\) data \((l > 5^\circ)\) with 0.68 \(\text{km s}^{-1}\) resolution outside the Galactic center region is shown in Figure 2 in linear and logarithmic scales. It was obtained by binning the data into 0.02 K wide bins. The brightness temperatures \((T_b)\) in the plot range from \(-2.5\) to 6 K. A few points in the survey are as hot as 17.4 K. Only data points from the observed ranges of position \((l > 5^\circ)\) and velocity listed in Table 1 are included in this histogram.

To gain insight about the true distribution of brightness temperatures if there were no telescope or receiver noise, a parametric model can be made of the distribution function. Suppose the true, noise-free distribution of brightness temperatures is a power law in brightness temperature, \(T\), plus a delta function at zero temperature:

\[
N_{\text{mod}}(T)\,dT = N_{\text{tot}} \times \left[ f_C \delta(0, T) + (1 - f_C) (T + C)^{\alpha - 1} \right] \,dT
\]

(for \(T \geq 0\)), where \(N_{\text{tot}} = 23,392,017\) is the total number of points in the survey, \(f_C\) is the fraction of points that have no emission, \(C\) is a parameter of the fit, and \(\alpha\) is the power law. The observed distribution of brightness temperatures would then be given by the convolution of this function with a Gaussian representing the noise:

\[
N_{\text{obs}}(T)\,dT = \int_{-\infty}^{\infty} N_{\text{mod}}(T - T')\,dT' \frac{1}{\sigma\sqrt{2\pi}} \exp \left( -\frac{(T' - T)^2}{2\sigma^2} \right) \,dT'
\]

and this function can be used to model the actual distribution of observed brightness temperatures. A \(\chi^2\) fit for the parameters of the model yields \(\sigma = 0.1065 \pm 0.0031\), \(f_C = 0.884 \pm 0.015\), \(C = 0.768 \pm 0.105\) K, and \(\alpha = 4.44 \pm 0.39\). The value \(\sigma \approx 0.11\) K can be compared with the 1 \(\sigma\) typical uncertainty in the UMass-SB Survey of 0.4 K (Sanders et al. 1986). Figure 3 shows a comparison of this fit with the observed data. The data from Figure 2 have been rebinned.
into logarithmic intervals. The points at negative brightness temperature have been folded about $T = 0$ K to allow both negative and positive brightness temperatures to appear on a logarithmic plot. The fit at negative temperatures shows that the noise in the survey deviates from a pure Gaussian: there is a tail to the distribution where a few points trail off to brightness temperatures as low as $-1$ K, as well as an excess of points near $T = 0$ K from spectra having better than specified noise. This is to be expected in a large survey in which the noise level is not perfectly controlled. The detected points at positive $T$ are not fit perfectly by a power law: there are too many points at brightness temperatures near $T \approx 2.5$ K and too few points at brightness temperatures $T > 10$ K for any power law to fit. The best-fit power law is surprisingly steep: $N(T) \propto (T + 0.768$ K)$^{-4.44}$. The large value of $C = 0.768$ K implies that there is no evidence for extensive low-level emission below the 0.1 K noise limit of the survey.

The $N_{\text{tot}}$ survey data points have a mean of $\langle T_{\text{sur}} \rangle = 0.037$ K and a variance of $\sigma_{\text{sur}}^2 = (0.229$ K)$^2$. These values do not have much physical significance, because they are dominated by the $\sim 88\%$ of the data that appears in the model distribution as a delta function at $T = 0$ K and appears in the survey data as a nearly Gaussian noise distribution around zero. If the survey were extended to include a larger region of the Galaxy with less CO emission, the mean would become smaller, and the variance would approach $\sigma^2$, the noise level of the survey. The mean and variance of the nonzero data alone can be estimated from the model of the data distribution, by discarding the points in the $T = 0$ K delta function:

$$\langle T_{\text{pos}} \rangle = \int_0^\infty T N_{\text{mod}}(T) dT / \int_0^\infty N_{\text{mod}}(T) dT = C(\alpha - 1) \Gamma(\alpha - 2) / \Gamma(\alpha) = 0.315$ K
$$

and

$$\sigma_{\text{pos}}^2 = \int_0^\infty (T - \langle T \rangle)^2 N_{\text{mod}}(T) dT / \int_0^\infty N_{\text{mod}}(T) dT = 2C^2(\alpha - 1) \Gamma(\alpha - 3) / \Gamma(\alpha) - \langle T_{\text{pos}} \rangle^2 = (0.48$ K)$^2$. 

These values are characteristic of points within the data set at positions where $^{13}$CO emission actually occurs; of the points in the survey data cube that have emission, the mean is 0.315 K and the variance is (0.48 K)$^2$.

Like all Galactic CO surveys to date, the data in this survey are spatially undersampled, in the sense that the spacing between adjacent beams is more than the half-beamwidth required by the Nyquist sampling theorem to prevent aliasing or the full beamwidth required to avoid flux errors. As shown in Table 1, some of the Galactic center region data are nearly fully sampled, with a 60’ grid and a 103’ beam; in this region, there is only slight aliasing of high spatial frequencies and no sampling error in the total flux. The majority of the data, however, are sampled on a grid whose spacing is 180’, so the sampling factor is only

$$\eta_{\text{samp}} = (\text{beam FWHM} / \text{grid spacing})^2 = 0.33 .$$

These data do not contain information about spatial wavelengths smaller than 6’, and there can be substantial error in the total flux of small sections of the survey.

When survey data are used to determine the total flux of a volume of $(l, b, v)$ space, what is done, in effect, is to average all the survey data points within that volume and then multiply that average by the volume under consideration to obtain the flux. The total number of independent samples within a volume of area $A$ and bandwidth $B$ is approximately

$$N_{\text{vol}} \approx \frac{A}{A_{\text{beam}}} \frac{B}{B_{\text{fil}}} ,$$

where $A_{\text{beam}}$ is the beam area and $B_{\text{fil}}$ is the width of a spectrometer filter. (As noted in §2.1, the spectrometer filter bandpasses have little overlap.) Of these, $\eta_{\text{samp}}N_{\text{vol}}$ points are measured in the survey, and $(1 - \eta_{\text{samp}})N_{\text{vol}}$ are not. It is assumed that the mean of the measured data points is the same as the mean of all $N_{\text{vol}}$ points; that is, that the mean of the unmeasured points is the same as the mean of the measured points. This assumption would introduce a fractional error in the total flux that is approximately

$$\frac{v_{\text{sur}}}{\langle T_{\text{sur}} \rangle} \sqrt{(1 - \eta_{\text{samp}})A_{\text{beam}}B_{\text{fil}} / A} \approx 0.12 \left( \frac{1}{A} \right)^{1/2} \left( \frac{1 \text{ km s}^{-1}}{B} \right)^{1/2} ,$$

if the unmeasured points were random samples of the same parent distribution as the whole survey. Since the brightness temperature actually has significant spatial and frequency correlation, this will tend to be an underestimate. We see that while the sampling error is small for regions of several square degrees or larger, it can be $\sim 100\%$ for regions a few arcminutes in size. In particular, a small cloud that happened to lie between grid points at the 6’ or 3’ spacings could be missed entirely. Such a cloud might be as large as $\sim 10^3 M_\odot$ if it were 15 kpc distant.

3. LONGITUDE-VELOCITY MAPS

We present the Bell Laboratories $^{13}$CO survey in the form of longitude-velocity maps at latitudes separated by 0.05° (Fig. 4). The reduced FITS cubes have been smoothed with a boxcar function to improve the signal-to-noise ratio. The boxcar function was 6’ wide in longitude and 2 km s$^{-1}$ wide in the velocity direction. The velocity range of the observations is visible in Figure 4 as the width in velocity of the gray dots, which are at the noise level of the survey. The color scale of the maps represents increasing brightness temperature in the order of gray, blue, green, yellow, and red. The color maps were generated using the WIP graphic package.

The velocity range of $-27$ to 147 km s$^{-1}$ for the region $5° < l < 45°$ is enough to encompass the whole velocity range of molecular gas emission, with the exception of one feature. This elongated feature at $(l, b, v) = (8°, -0.5, 147$ km s$^{-1})$ in Figure 4 extends beyond the positive velocity limit of this survey. The Columbia survey shows this feature extending to 220 km s$^{-1}$ (Dame et al. 1987).

The following are some of the principal characteristics of the survey:

1. It is found that only $(1 - f_2) = 12\%$ of the pixels in $(v, l, b)$ three-dimensional space are responsible for the $^{13}$CO emission over the region surveyed. This number would be even smaller for a survey that was more extensive in $b$ or...
Fig. 4—Longitude-velocity color scale maps at all latitude grid points. The color map represents increasing intensity as gray, blue, green, yellow, and red. The velocity range of the observations is delimited by gray dots representing the noise in the data.
Fig. 4—Continued
Figure 4. Continued
Fig. 4—Continued
Fig. 4—Continued
Fig. 4.—Continued
Fig. 4—Continued
Fig. 4—Continued
Fig. 4—Continued

Galactic Longitude

\( b = 0.70 \)

\( V_{LSR} \) (Km/s)
that had larger velocity coverage. About 39% of the total survey emissivity arises in three-dimensional pixels having brightness temperature above $T^*_{\text{K}} > 1$ K ($10\sigma_{\text{rms}}$), which is to say

\[
\int_{T_{\text{K}}^*}^{\infty} N(T)T \,dT = 0.39.
\]

Similarly, 16% of the survey emissivity arises in pixels above 2 K and 3.4% arises in pixels above 4 K. These values can be compared with the UMass-SB $^{12}$CO survey's 17.5% above 4 K ($10\sigma_{\text{rms}}$).

2. A comparison with the UMass-SB survey shows that at any point in the survey, the $^{12}$CO emission is related to the $^{13}$CO emission. That relationship can be expressed as a monotonic function with scatter (Stark et al. 1983). Even though the $^{13}$CO is roughly predictable from the $^{12}$CO emission in a statistical sense, features of the clouds are more clearly delineated in $^{13}$CO than $^{12}$CO. In Figure 5, an example of $^{12}$CO and $^{13}$CO longitude-velocity maps for the region $33.5 < l < 36.5$ at $b = 0.1$ is shown. The $^{12}$CO map was also taken using the Bell Laboratories 7 m telescope, but it differs only slightly from the UMass-SB survey data. In the $^{12}$CO map, cloud boundaries are not clear, and clumps are not unambiguously delineated. In the $^{13}$CO map, clouds are more readily distinguishable. The cloud identification using the $^{13}$CO line is much easier than that using the $^{12}$CO line, since the $^{13}$CO lines are more optically thin, so that the cloud boundaries can be determined at a lower threshold brightness temperature.

3. The relative weakness of $^{13}$CO emission compared with $^{12}$CO emission does not necessarily mean that clouds are missed in the survey, since the noise level is small. We made a catalog of clouds identified in the UMass-SB survey with a 4 K threshold level. All these clouds are also present in a catalog made from the Bell Laboratories $^{13}$CO survey with a 0.3 K threshold, and 99.4% are present in a catalog made with a 0.5 K threshold.

4. Using the modified cloud identification code within IRAF (Lee, Jung, & Kim 1997), $^{13}$CO clouds have been identified and cataloged as a function of threshold brightness temperature. There are 1250 molecular clouds identified with a 1 K threshold, 560 clouds with a 2 K threshold, and 240 clouds with a 3 K threshold. Clouds with the hottest cores [$T^*_K(13CO) > 3$ K] are restricted to the 6 kpc molecular ring ($l < 40^\circ$) and the $l = 80^\circ$ region. It is found that the peak brightness temperatures in the Galactic center ($|l| < 5^\circ$) are not as high as those in the molecular ring (see Fig. 4; $b = 0.3$ to $-0.3$). In addition to cloud identification, cloud core regions can also be located within the cloud complex. A sample spectrum centered on $(l, b) = (34.25, 0.1)$ is presented in Figure 6. While there are saturated and self-absorbed features in $^{12}$CO emission (thin solid line), the $^{13}$CO lines show clean, nearly Gaussian profiles. At the location $(l, b) = (34.25, 0.1)$, the core region is obvious in the $^{13}$CO map, while it is not apparent in the $^{12}$CO map. Dense core regions can be located using this $^{13}$CO survey and then combined with existing $^{12}$CO data. The optical depth of $^{13}$CO can be estimated for each channel and pixel from the ratio of the $^{12}$CO and $^{13}$CO brightness assuming LTE. This estimate gives a lower limit to the true optical depth under non-LTE conditions.

5. The $^{13}$CO emission toward the 6 kpc molecular ring region has more contrast than does the $^{12}$CO emission (Sanders et al. 1986; Clemens, Sanders, & Scoville 1986). Note in particular that the brightest cores are concentrated in elongated loops corresponding to the spiral arms (see Fig. 4; $20^\circ < l < 50^\circ$, $b = 0.0$).

6. Little emission occurs in the outer Galaxy; there are few detections at negative velocities in the range $20^\circ < l < 80^\circ$, for all survey latitudes ($b = -1.0$ to $1.0$). The Perseus arm does appear as a distinct feature at $l > 80^\circ$ and negative velocities. In Figure 7, plots of the $^{13}$CO integrated intensity are represented for the whole range of velocities observed. Nine latitude slices have been selected for display. The resolution in longitude is $3^\circ$, and the latitudes are indicated on the top left corners of the plots: $1^\circ, 0.7, 0.5, 0.25, 0.0, -0.25, -0.5, -0.7, -1.0$. There are no data in the Galactic center region $|l| < 5^\circ$ for $b = 1.0, 0.7, -0.7, -0.5$.

7. Much of the gas in the Galactic center region ($|l| < 5^\circ$) occurs at velocities forbidden to circular orbits and is likely to be in eccentric orbits about the center (Bally et al. 1987; Binney et al. 1991). This gas has large line widths (see Fig. 4; $b = -0.6$ to $0.6$). In addition to these well-known Galactic center features, there are several clouds outside the Galactic center with line widths as large as 20 km s$^{-1}$ that are confined to a few adjacent grid points. Two examples are seen in Figure 4 at $(l, b) = (43.15, 0.05)$ and $(26.65, 0.60)$.

8. Spiral structure is readily apparent in the survey from the emission of GMCs. Within the volume delimited by the range of velocities permitted by Galactic rotation, there are large volumes showing these clouds (e.g., Fig. 4; $33^\circ < l < 35^\circ$, $-0.25 < b < 0.25$, $90 < v < 120$ km s$^{-1}$), and there are otherwise similar volumes within the interarm regions that have no GMCs (e.g., Fig. 4; $35^\circ < l < 37^\circ$, $-0.25 < b < 0.25$, $85 < v < 115$ km s$^{-1}$).

9. Small clouds are found at all permitted velocities inward of the solar circle. This is not the case outside the solar circle. There is a complete absence of detected $^{13}$CO emission in the interarm region between the local molecular gas and the Perseus arm ($90^\circ$--$117^\circ$) at velocities from $-20$ to $-40$ km s$^{-1}$ (see Fig. 4 at all values of $b$; see also Cohen et al. 1980; Heyer et al. 1998). Cohen et al. (1980) argue that this gap does not necessarily mean that molecular gas is nonexistent in the interarm region; such gas could either be diffuse, cold, or in small clumps that could escape detection. Heyer et al. (1998) showed, however, that not even small clumps are detectable in $^{12}$CO in this region, implying a complete absence of molecular material. In an interarm region somewhat closer to the Galactic Center, our survey data show small cloudlets in the interarm region from $l = 60^\circ$--$70^\circ$. In the molecular ring at $l \sim 25^\circ$, the interarm regions are filled with clouds.

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Fig. 5.—Example of longitude-velocity $^{12}$CO and $^{13}$CO contour maps at $l = 33.5$–$36.5$, $b = 0.1$. The $^{12}$CO contours are multiples of 1.0 K up to a maximum contour of 12 K. The $^{13}$CO contours are 0.3, 0.6, and 1.0 K, followed by increments of 0.6 K up to a maximum contour of 106.4 K.
Fig. 6. $^{12}$CO and $^{13}$CO composite spectra centered on and around $(l, b) = (34.25, 0.1)$. The thin solid line represents $^{12}$CO, and the thick solid line represents $^{13}$CO.
Fig. 7.—Plots of the $^{13}$CO intensity integrated over the whole range of velocity, plotted against longitude at the indicated latitude: $\pm 0.0, 0.7, 0.5, 0.25, 0.0, -0.25, -0.5, -0.7$, and $-1.0$. The resolution in longitude is $3^\circ$. 
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