THE BELL LABORATORIES CO SURVEY: STAR FORMATION IN SPIRAL ARMS

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ABSTRACT. We present a galactic survey which to date consists of 47,000 positions covering $-3^\circ < l < 122^\circ$, $-1^\circ < b < 1^\circ$, observed in the $J=1 \rightarrow 0$ line of ^{13}CO to an rms noise level of 0.15 K in 0.68 km s^{-1} channels, using the 7 m antenna at Crawford Hill. Maps made from the survey data show a clear difference between spiral arm and interarm regions. The signature of spiral structure on kiloparsec scales is the presence in galactic survey data of voids in l, b, v space which contain many times fewer Giant Molecular Clouds (GMCs) than do adjacent regions of similar size. The difference between arm and interarm regions in the inner galaxy is manifested only in the GMCs — small clouds are present throughout. These results are based on catalogs of clouds and their estimated sizes in ^{13}CO. We suggest that GMCs are formed as interstellar gas enters a spiral arm, and that they break up into small molecular or atomic clouds as the gas leaves the arm.

The 7 meter antenna at AT&T Bell Laboratories, Crawford Hill is being used to make a CO survey of the Galaxy (Stark 1979, 1983, Knapp, Stark and Wilson 1985). About 1/5 of the survey has now been completed, and in this talk we discuss a preliminary result: we show that Giant Molecular Clouds (GMCs) are absent from some parts of the survey. We suggest that the voids in the GMC distribution are the regions between the spiral arms of our galaxy. These interarm regions are not empty of molecular material, but contain many small clouds.

The Bell Labs survey was designed to resolve and detect clouds of about $10^3\ M_\odot$ or bigger, anywhere in the galaxy. The parameters of the survey are:

1. Both ^{12}CO and ^{13}CO are observed. We have found that the ^{13}CO data are significantly different from the ^{12}CO in the galactic center region and towards Giant Molecular Clouds, and that the ^{13}CO data is easier to interpret (Stark, Penzias and Beckman 1983). We have therefore concentrated on ^{13}CO.
2. Sensitivity — 0.15 K rms in 0.68 km s^{-1} channels for ^{13}CO, 0.3 K rms in 0.65 km s^{-1} channels for ^{12}CO. The centers of resolved molecular clouds are almost always more than three times brighter than these noise levels. The brightest points are about 10 K in ^{13}CO and about 20 K in ^{12}CO.
3. Coverage — the region covered so far is $-5^\circ < l < 122^\circ$, $-0.5^\circ < b < 0.5^\circ$. Eventually, the survey will be extended to higher latitudes.
4. Sampling — all of a 6′ grid has been observed, and most of a 3′ square grid is complete. It may be possible to fully sample the survey with our 1.′7 beam.

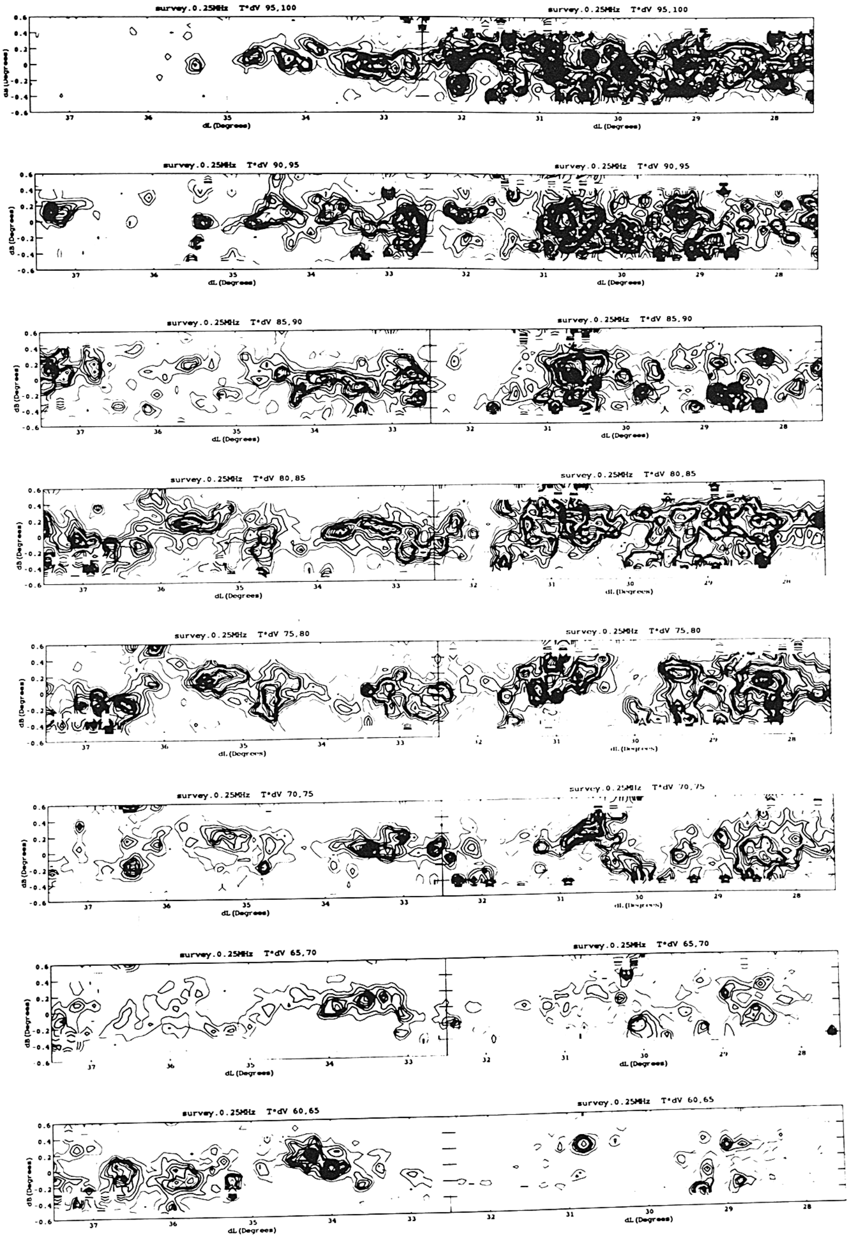

Figure 1. Contour maps of ^{13}CO integrated brightness from the Bell Laboratories CO Survey (Stark 1983). Each map covers $l = 27^{\circ}.5$ to $37^{\circ}.5$, $b = -0^{\circ}.5$ to $0^{\circ}.5$. The map at top is centered at $v = 97.5\,\mathrm{km\,s^{-1}}$, and each successive map is at 5 $\mathrm{km\,s^{-1}}$ lower velocity. Contour levels are spaced at 0.5 $\mathrm{K{\cdot}km\,s^{-1}}$ intervals. Note the absence of GMCs at $l = 30^{\circ}$, $v = 65\ \mathrm{km\,s^{-1}}$ and $l = 36^{\circ}$, $v = 90\ \mathrm{km\,s^{-1}}$.

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5. Calibrated within 5% of absolute temperature scale, using calibration loads and standard sources.
6. Accurate beam pattern — the Gaussian central lobe contains $\gtrsim 87\%$ of the antenna response; less than 5% of the response is from Milky Way emission not in the central lobe.

So far, we have collected 47,000 ^{13}CO spectra. We can collect about 2000 spectra per day on cold, clear winter days. The full survey is planned to contain more than a quarter-million spectra.

Galactic survey data is a scalar function of three dimensions: galactic coordinates, l and b, and radial velocity, v. GMCs can be recognized and located in this space. A GMC is a ≈ 50 pc region, emitting a peak CO line antenna temperature in excess of a few degrees K, where the line velocity does not vary more than a few km s^{-1}. It is possible to make a complete catalog of all GMCs in areas of the sky covered by the survey. When this is done, it is found that there exist large voids, containing few or no GMCs (Stark 1979, 1983). These voids are also seen in the Columbia University survey (Cohen *et al.* 1980). The voids are at velocities that are permitted by galactic rotation, so that they would be populated by GMCs if the GMCs were uniformly distributed in space and rotating in circular orbits; they should contain numbers of GMCs comparable to adjacent regions of similar size, but they do not. Low mass molecular clouds are present throughout the voids and the adjacent regions. These low mass clouds are usually not detected in the Columbia survey, because of its greater noise level and larger beam area.

Figure 1 shows a small section of the survey, covering material about 5 kpc from the galactic center, between $l = 27.^\circ5$ and $37.^\circ5$. This is the peak of the Molecular Ring, the local maximum in the density of molecules outside the galactic center (Solomon and Sanders 1980). In this figure, 1° corresponds to about 100 pc, and the various maps are separated by 5 km s^{-1} intervals, so a GMC will appear in one or two maps, and and will appear about $0.^\circ3$ in linear size, possibly with an outer envelope extending beyond $0.^\circ5$. There are over twenty GMCs near the tangent point of the scutum arm at $l = 31^\circ$, $v = 95$ km s^{-1}, while an adjacent region of comparable size near $l = 31^\circ$, $v = 65$ km s^{-1} has none. There are numerous small clouds, less than 10 pc across and $< 10^{4.5}$ $M_\odot$, in the interarm region at $l = 31^\circ$, $v = 65$ km s^{-1}. The position $l = 36^\circ$, $v = 92.5$ km s^{-1} is a permitted velocity slightly less than the tangent velocity at that longitude, so it should be a region in l, v space where there is considerable velocity crowding. Nevertheless, there are no GMCs near this position. Compare this region to $l = 33^\circ$, $v = 92.5$ km s^{-1}, where there are six nearby GMCs.

The voids exist because GMCs are concentrated in the spiral arms, and they are on non-circular orbits. The contrast between the voids and their surroundings is so great that purely kinematic explanations cannot apply. CO surveys differ in this respect from HI surveys. Burton (1970) has pointed out that the l, b, v structure of HI surveys can be explained by a uniform spatial distribution of gas with appropriate choice of streaming velocities; however, the the arm-interarm contrast in HI much less than that of the GMCs, so this possible explanation does not apply to GMCs. The voids in the GMCs must be several square kiloparsecs in size, looking down on the disk of the galaxy, and mapping velocity into distance by the galactic rotation law. Since GMCs are not present in interarm regions, their lifetimes must be less than the time it takes gas to cross an arm, about 100 million years. If GMCs build up in less than this time, say 30 million years, the only plausible source of material is the small molecular clouds found throughout the interarm regions. Indeed, some GMCs appear to be loose associations of smaller clouds (Blitz and Stark 1986). Kinematic evidence suggests that GMCs are formed by agglomeration of small clouds (Stark 1983).

Giant Molecular Clouds play an important role in spiral structure. The external manifestations of spiral structure in galaxies, namely dust lanes, young stars, and gas, are different aspects of GMCs and the star formation processes within them. GMCs are strongly concentrated in the spiral arms of other galaxies. In the Milky Way, it is impossible to be sure where the spiral arms are, because of our peculiar perspective, but GMCs are concentrated in some regions, and absent in others. These voids are the signature of spiral structure in the Milky Way.

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KUTNER: I believe what you are saying, but there are some who contend that you cannot interpret holes in l-v space as representing holes in 2-dimensional space because of streaming effects. Could you comment on that?

STARK: The contrast in Giant Molecular Clouds between the arms and the interarm regions is very large some large values of l,b,v, space have *no* GMC's. I think this contrast is too large to be explained by streaming. Also, if there is streaming (i.e. divergence in the fluid flow) then there must be density enhancements.

ELMEGREEN: The term "giant molecular clouds" has often been applied to Orion-type clouds which have a mass of approximately 10^5 $M_\odot$. Such clouds, and clouds of lower mass too, seem to occur in both the arm and interarm regions of galaxies. The *larger* clouds in the spiral arms should have a different name, such as "superclouds", to avoid confussion. These larger clouds have masses of 10^6 - 10^7 $M_\odot$. Then your statement that density waves trigger the formation of "giant molecular clouds" would not be misinterpreted as a triggering of Orion type clouds. Spiral density waves seem to trigger only the formation of "superclouds", possibly by the gravitationally-driven coagulation of Orion-type and smaller clouds.

STARK: In these voids , there are no clouds quite as large as the Orion Molecular Cloud. There certainly are "spiral arm spurs" between the arms: the arms in our galaxy are not regular. There are Orion-sized clouds between the arms. My point is that there are large regions which do not contain even small GMC's like the Orion molecular cloud. I agree that the very large Giant Molecular Cloud Complexes in the spiral arms are probably formed by agglomeration of Orion-sized GMC's and smaller clouds.

GORDON: Is it still true that the newer, more sensitive CO surveys still do not show much material between 2 and 4 kpc from the nucleus? If so, cannot this be an effect due to the inability of a density wave to penetrate a resonance radius at 4 kpc?

STARK: Yes, it is still true that there are only a few molecular clouds between 2 and 4 kpc, and yes, there may be a large-scale dynamical reason, as you have suggested.

GIANT MOLECULAR CLOUDS IN THE GALAXY: THE MASSACHUSETTS-STONY BROOK CO GALACTIC PLANE SURVEY

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The CO Galactic Plane Survey consists of 40,572 spectral line observations in the region between l = 8° to 90° and b = $-1\overset{\circ}{.}05$ to $+1\overset{\circ}{.}05$ spaced every 3 arc minutes, carried out with the FCRAO 14-m antenna. The velocity coverage from -100 to +200 km/s includes emission from all galactic radii. This high resolution survey was designed to observe and identify essentially all molecular clouds or cloud components larger than 10 parsecs in the inner galaxy. There are two populations of molecular clouds which separate according to temperature. The warm clouds are closely associated with H II regions, exhibit a non-axisymmetric galactic distribution and are a spiral arm population. The cold clouds are a disk population, are not confined to any patterns in longitude-velocity space and must be widespread in the galaxy both in and out of spiral arms. The correlation between far infrared luminosities from IRAS, and molecular masses from CO is utilized to determine a luminosity to mass ratio for the clouds. A face-on picture of the galaxy locating the warm population is presented, showing ring like or spiral arm features at R $\sim$ 5, 7.5 and 9 kpc. The cloud size and mass spectrum will be discussed and evidence presented showing the presence of clusters of giant molecular clouds with masses of 10^6 to 10^7 $M_\odot$. The two populations of clouds probably have different star forming luminosity functions. The implication of the two populations for star formation mechanisms will be discussed.