

CO OBSERVATIONS OF SPIRAL STRUCTURE AND THE LIFETIME OF GIANT MOLECULAR CLOUDS

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Observations of CO emission at $\ell=0$ to 70° , $|b| \leq 1^\circ$ are analyzed to give a map of the molecular cloud distribution in the galaxy as viewed from the galactic pole. From the fact that this distribution shows no obvious spiral pattern we conclude that the giant molecular clouds sampled in the CO line are situated in both arm and interarm regions and they must last more than 10^8 years. A similar age estimate is deduced from the large mass fraction of H_2 in the interstellar medium in the interior of the galaxy. An implication of this longevity is that the great masses of these clouds may be accumulated through cloud-cloud collisions of originally smaller clouds.

1. INTRODUCTION

One of the great expectations of the 2.6-mm CO line is that its distribution will delineate the spiral structure of the Milky Way with a clarity not obtained in either 21-cm line studies or radio observations of HII regions. The line is highly selective towards the densest interstellar clouds where star formation must occur; it is ubiquitous and easily detected in these regions; and the angular resolution of 1 arc-minute which is available with existing telescopes is smaller than typical cloud sizes even for clouds on the far side of the galactic center.

The giant molecular clouds revealed by CO surveys of the galactic plane (Scoville and Solomon 1975; Burton et al. 1975; Burton and Gordon 1978) are a new class of interstellar cloud which constitutes the dominant mass component of the interstellar medium in the interior of the galaxy. Individual masses are typically $10^5 - 10^6 M_\odot$. Their total number is estimated to be about 5000; most of them are situated in an annulus at 4 to 8 kpc galactic radius (cf. Solomon - this volume).

Our picture for the evolutionary history of the giant molecular clouds and the role played by the spiral shock in precipitating star formation will be strongly influenced by whether the clouds are situated

only within spiral arms or whether they are also found just as frequently in interarm areas. The evidence I shall present here indicates that they are found in both regions. A consequence of this is that the clouds must exist as entities for very long times - perhaps 10^9 years rather than 10^7 years as previously assumed, and their large masses can be plausibly accounted for by growth occurring as a result of cloud-cloud collisions. Since the protostellar gas flowing into the spiral arm shock is therefore already composed of high density clouds; the role of the shock in provoking star formation may be substantially less than previously imagined.

2. A "FACE-ON" PICTURE OF THE GALAXY

By virtue of its broad latitude coverage, the survey of Solomon, Scoville, and Sanders (1978) affords an excellent opportunity to trace large scale galactic features such as spiral arms or cloud clusters which do not necessarily maintain a constant latitude over their full longitude extent. Approximately 1100 points in the inner galactic plane at longitudes -5° to 90° were observed with the NRAO 36-foot antenna and the recently completed 45-foot telescope at the University of Massachusetts. Spectra were taken both in the plane and out to $b = \pm 1.5^\circ$ so as to cover at least one scale height of the cloud distribution for any gas at greater than 2 kpc distance.

In transforming the CO data in the l/v plane into galactocentric coordinates of radius and azimuth, there results an ambiguity in the azimuthal angle for clouds interior to the solar circle. In the present survey the extended latitude coverage enables us to resolve the ambiguity for many cloud complexes. Since the scale height deduced for molecular clouds is 70 - 100 pc, most of the features we observe at $|b| > 0.35$ are probably at the near-point azimuth.

The "face-on" distribution of CO emission at high latitudes and at low latitudes are shown separately in Figure 1. In the first figure no attempt was made to resolve the distance ambiguities; each CO feature is shown at both its near and far point locations. The mapping of the observed emission from l/v coordinates to $\tilde{\omega}/\phi$ employed the Schmidt rotation law which has been found to apply within $5 \text{ km}\cdot\text{s}^{-1}$ to the molecular gas.

In Figure 2 we have attempted to resolve the distance ambiguities by comparison of high and low latitude data in Figure 1 and by identification of particular features with galactic HII regions for which the ambiguity has been resolved from absorption line studies. The ambiguities were resolved for all strong features, but for many of the weak features where the assignment was unclear both positions remain.

There is excellent correlation between the positions of giant HII regions (cf. Georgelin and Georgelin 1976) and giant molecular clouds. The correlation is in the sense that nearly all HII regions for which

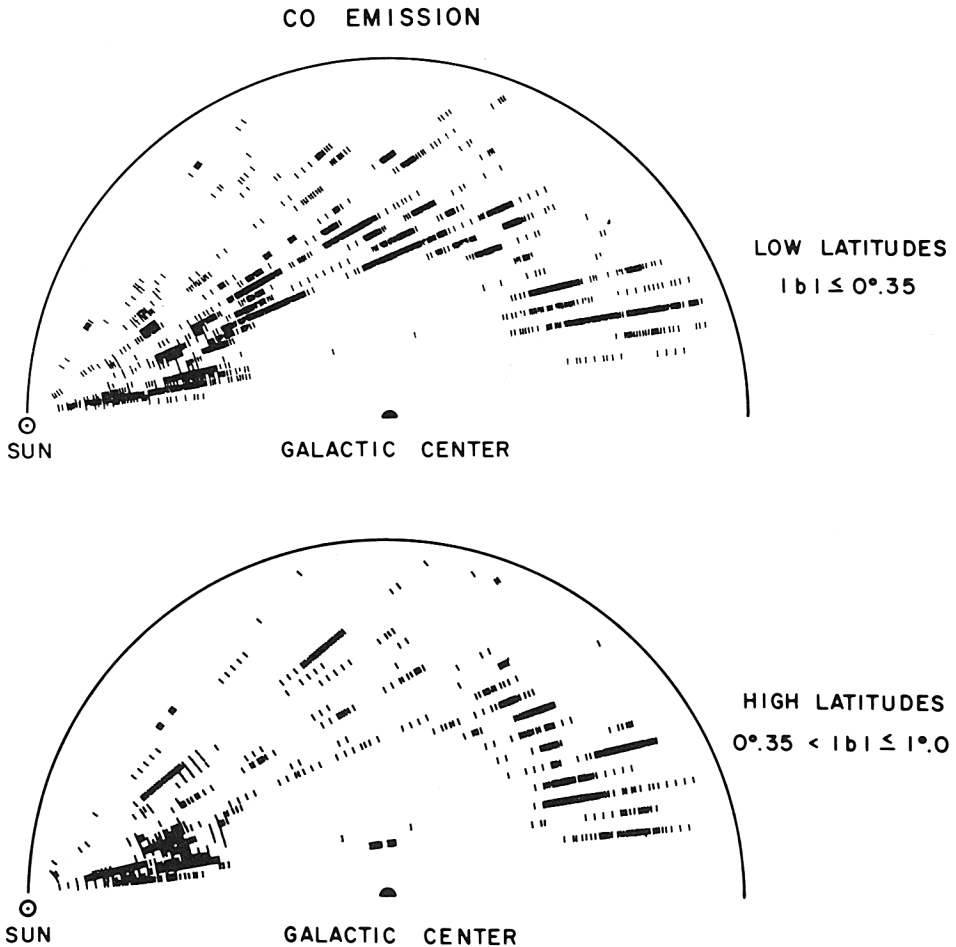


Figure 1: The relative distribution of CO emission in the galaxy at $\ell=0$ to 70° as viewed from the North galactic pole. Only strong features with $T_A^*/\eta > 5^\circ\text{K}$ have been plotted. Each region is shown at both near and far points along the line-of-sight calculated from the Schmidt rotation law. High and low latitude data are shown separately to enable distance determinations.

we have CO data within $1/4^\circ$ have a CO counterpart with similar radial velocity. It is clearly not the case that every giant molecular cloud has an associated HII region since we count in this survey alone many more separate clouds than there are known giant HII regions.

The two major spiral features deduced from 21-cm line observations of the northern hemisphere ($\ell=0$ to 90°) are the Scutum and Sagittarius arms which are tangential to the line of sight at $\ell=33^\circ$ and 50° with radial velocities of 100 and $60 \text{ km}\cdot\text{s}^{-1}$. Concentrations of CO emission

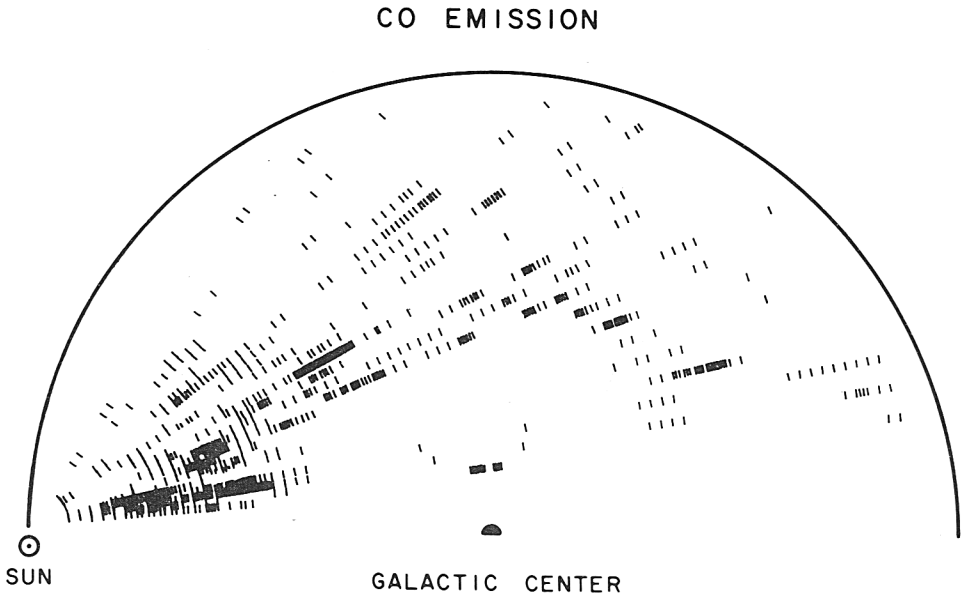


Figure 2: The relative distribution of strong CO features ($T_A^*/\eta > 5^\circ\text{K}$) at $|b| \leq 1^\circ$ is shown in a face on view of the galaxy. Distance ambiguities are resolved where possible by comparison of the high and low latitude emission data in Figure 1 and by identification of features with HII regions at known distances.

corresponding to the tangential directions of these two arms are clearly seen in Figure 2 at a distance about 7 kpc from the sun. In the CO data neither of these features may be traced over more than 10° of longitude.

It is clear from the absence of a recognizable spiral form in Figure 2 that most of the clouds cannot be situated within a regular pattern of spiral arms. It is difficult to estimate the percentage of clouds in arms as compared to that between arms for two reasons. First, there is not any strong agreement among previous observers of spiral structure as to precisely how the 21-cm features and HII regions should be linked up into arms. Secondly, with two arms running through the observed l/v space, a good fraction of the CO emission regions should fall at l/v locations close to the presumed spirals even if they were randomly situated in the galactic plane. Examples of features definitely not in the spiral arms are, however, found at $l=40^\circ$, $v = 85 \text{ km}\cdot\text{s}^{-1}$; $l=24^\circ$, $v = 105 \text{ km}\cdot\text{s}^{-1}$; and the low velocity features and $l > 20^\circ$.

3. THE LIFETIMES OF MOLECULAR CLOUDS

Based upon the detection of molecular clouds in interarm regions 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. Since the clouds last well into the interarm regions we conclude that their ages are at least 10^8 years. Perhaps even more persuasive is an argument based upon the observational determination that the greatest fraction of the interstellar hydrogen in the interior of the galaxy is molecular rather than atomic or ionic. If the interstellar medium constantly cycles gas through the H_2 , HI, and HII phases and the relative abundances are maintained in a steady state, then continuity demands that the mass flow rate out of the H_2 phase (M_{H_2}/τ_{H_2}) must equal the flow rate out of the HI and HII phases into H_2 ($M_{HI} + M_{HII}/\tau_{HI} + \tau_{HII}$). Since M_{H_2} is found to be greater than $M_{HI} + M_{HII}$, continuity requires $\tau_{H_2} > \tau_{HI} + \tau_{HII}$. The timescale for a typical low density atomic or ionized hydrogen region to exist is probably at least 10^7 years and generally approaches 10^8 years in the interarm regions so that τ_{H_2} must be at least 10^8 years. It is thus deduced from two independent lines of reasoning that the giant clouds last at least 10^8 years and may well last 10^9 years since it is unclear what process is capable of disrupting them when they are so massive.

4. COLLISIONAL GROWTH OF MASSIVE CLOUDS

Once it is recognized that these clouds are extremely old, it becomes plausible that their very large masses, typically $4 \times 10^5 M_\odot$ may be built up through the mechanism of cloud-cloud collisions (Scoville and Hersh 1978). The timescale for cloud collisions in the interior of the galaxy ($\tilde{\omega} = 4$ to 8 kpc) is 3×10^8 years using current estimates for the cloud parameters. A high efficiency for binding of the two colliding clouds is expected inasmuch as their mean velocities are typically comparable with the $10 \text{ km}\cdot\text{s}^{-1}$ escape velocity from a single cloud. They will still probably coalesce even in cases where the collision velocities are large since the excess kinetic energy can be dissipated rapidly via radiation in the H_2 rotational transitions. In the absence of a mechanism decreasing the mass of H_2 clouds, we therefore expect that they can double their masses within the period of each collision which is presently comparable with lower limits to the cloud lifetime.

It is clear that the mass buildup via accretion cannot go unchecked for more than 10^9 years lest all the clouds become too massive. There must be one or more processes which remove H_2 from the clouds at an average rate equal to that provided by collisions. Though various mechanisms such as supernova explosions may be capable of completely dispersing a cloud of $10^3 - 10^4 M_\odot$ in a single event this is not possible for the very massive giant molecular clouds. For such a cloud of $4 \times 10^5 M_\odot$ the escape velocity is about $10 \text{ km}\cdot\text{s}^{-1}$; a single event would therefore need to supply a momentum of $4 \times 10^6 M_\odot \text{ km}\cdot\text{s}^{-1}$ or it must ionize $4 \times 10^5 M_\odot$ at an average density of 10^3 H nuclei per cc. Since these requirements far exceed the capabilities of supernova or common O-stars, the process of removing H_2 from clouds is more likely in the form of "chipping away" at the cloud rather than catastrophic occurrences.

Formation of massive stars which subsequently ionize an HII region or undergo supernova explosion while in the cloud can lead to a decrease in the mass of H_2 within the giant clouds. The mass-loss rates of these processes must be added to that associated with steady conversion of H_2 gas into stars. Of these processes, the most important are probably the ionization by O-stars and the absorption of H_2 into newly formed stars. The former rate is very difficult to estimate with reliability; the latter is estimated at $\sim 2 M_\odot \text{ yr}^{-1}$ for the entire galaxy (Scoville and Hersh 1978). If this galactic star formation rate is evenly divided amongst the total of about 5000 giant molecular clouds in the galaxy, we find that the rate of collisional growth of molecular clouds is very nearly balanced by the rate of star formation.

5. CONCLUSIONS

The evolutionary model suggested here represents a radical departure from the notion that dense star-forming clouds are the result of compression by a galactic density-wave travelling through a low density medium. Except for the higher rate of star formation which clearly does occur when the clouds pass through a spiral arm, the large scale cloud structure may be effected very little. If the removal of gas from the clouds is piecemeal through star formation, rather than catastrophic, we should then picture a cloud as an entity which survives even longer than 10^9 years though it does not retain a typical gas element longer.

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DISCUSSION

Woodward: Is the observed number of giant molecular clouds in interarm regions consistent with a dynamic model of cloud motions and with the long cloud lifetime you are suggesting? If clouds are long lived, one might expect to see about half of them in interarm regions.

Heiles: From observational data can one appeal to large-scale kinematics (such as rotation) to keep the star formation rate down?

Scoville: We have not yet analyzed the data to determine if many clouds show significant rotational velocity gradients. It will be difficult to discriminate between rotational gradients and the random velocity changes which occur quite generally within these clouds.

Rohlfs: If you argue that the giant molecular clouds are old ($\tau > 10^8$ y), and on the other hand you show that they are gravitationally bound, what prevents these clouds from collapsing?

Scoville: It is clear that there is some mechanism restraining the observed clouds from free-fall collapse. It is also clear from observations of external galaxies that although dust clouds exist between the spiral arms, the spiral arm shock does provoke rapid formation of massive stars. One property we have not been able to measure yet is the magnetic field strength; it is possible that there is a significant magnetic pressure restraining the clouds from collapse. (This appeals to the well-known astronomical maxim that if you can't measure an effect, it could be important.)

Van Woerden: I might remind Dr. Scoville that it takes only 10^7 years, at an expansion velocity of 10 km s^{-1} , for an association to grow from 0 to 200 pc diameter.

Shuter: It seems to me that the best way to treat CO data in an attempt to observe spiral structure is to average profiles that are far enough apart for the individual clouds to be uncorrelated, but near enough that the galactic rotation has not changed significantly.

Cesarsky: Could it be that molecular clouds can exist for some time without making stars, so that the age of molecular clouds is even larger than the age you quoted, based on destruction by an OB association?

Elmegreen: There are no observations for the lifetimes of giant clouds before the onset of massive star formation. One must make a distinction between the lifetime of the molecules themselves, which may be quite long (10^9 years) and the lifetimes of the cloud complexes as physical self-gravitating entities, for which I suggest a maximum of ~ 50 million years. This long time is already 100 times the cloud's dynamical (free-fall) timescale. It is difficult to imagine a delay in star formation for a time much longer than this. Of course, once massive star formation occurs, the cloud destruction is relatively rapid.