THE ASTROPHYSICAL JOURNAL, 317:L63–L67, 1987 June 15

MOLECULAR SPIRAL STRUCTURE IN M51

K. Y. LO
Department of Astronomy, University of Illinois; and California Institute of Technology
AND
R. BALL,[1] C. R. MASSON, T. G. PHILLIPS, S. SCOTT, AND D. P. WOODY
Owens Valley Radio Observatory, California Institute of Technology
Received 1986 November 5; accepted 1987 April 6

ABSTRACT

Observations of CO emission at 7″ resolution from the central 2′ × 1′ of M51 show directly that molecular gas, probably complexes of relatively warm giant molecular clouds, is strongly confined to spiral arms outlined by prominent dust lanes and radio continuum ridges. Molecular clouds must also populate fairly uniformly the interarm regions. The arm-to-interarm $N(H_2)$ ratio, averaged over 300 pc, is at least 3. These observations suggest that in the inner region of M51 molecular clouds coalesce to form bigger complexes in the presence of a spiral gravitational potential, and that such complexes are redispersed into molecular clouds upon leaving the arms. The spiral arm molecular *cloud complexes* last $\leq 5 \times 10^7$ yr, the arm crossing time, and molecular clouds probably last as long as the interarm crossing time which is $\leq 1.0 \times 10^8$ yr at 45″ (2.2 kpc) from the center. Coherent molecular structure along the spiral arm as large as 3 kpc can be identified. There is a minimum of CO emission within the central 600 pc. Noncircular motion of the CO gas is evident from the velocity field.

Subject headings: galaxies: structure — interstellar: molecules

I. INTRODUCTION

The spiral structure of late-type galaxies are most strikingly outlined by "Population I" objects, i.e., young blue stars, H II regions, and dust lanes. Molecular gas, being the raw material for star formation, is thus an important ingredient of such galactic structure. Observing the distribution of the molecular gas, its physical properties, its relationship to other components of the interstellar medium and to the spiral arms would help the understanding of the cloud formation mechanisms and the underlying cause of spiral structure.

Delineating spiral structure in our Galaxy is, by necessity, an indirect process which often leads to ambiguous results, although the inferences on the molecular gas distribution in our Galaxy are now converging (e.g., Solomon, Sanders, and Rivolo, 1985; Dame *et al.* 1986). External galaxies present a more favorable perspective for directly identifying spiral structure, but until recently CO observations have been limited by the 30″–60″ resolution of single telescope observations, inadequate to resolve the spiral arms except in M31 (Stark 1985).

The well-known Whirlpool galaxy (M51), a nearly face-on Sc galaxy showing very well-defined spiral structures, has been extensively studied (e.g., Toomre and Toomre 1972; Tully 1974; Rose and Searle 1982). In particular, single-telescope CO observations have been carried out by various groups (Rickard and Palmer 1981; Scoville and Young 1983; Rydbeck, Hjalmarson, and Rydbeck 1985). Rydbeck *et al.* observed at 33″, the highest resolution so far achieved, and they inferred the presence of spiral structure in the CO emission by model-fitting the spectral profiles.

We present here 7″-resolution (300 pc at a distance of 9.6 Mpc) interferometric observations of the central region of M51 that show directly spiral structure in the CO emission. Because of the positional accuracy of interferometric measurements, we can also reliably demonstrate the spatial correlation of the CO emission to dust lanes and the radio continuum arms seen at $\lambda = 6$ cm.

II. OBSERVATIONS

The observations were made using three configurations of the Owens Valley millimeter-wave interferometer (Masson *et al.* 1985). The synthesized beam is 7″.5 × 6″ (PA = −20°). Two fields (FWHP ≈ 65″) 20″ north and south of the center of M51 were observed, with the 32 channel 1 MHz (2.6 km s^{-1}) filter-bank centered on V(LSR) = 430.3 km s^{-1} and 508.4 km s^{-1}, respectively. Zero-spacing flux density was obtained with one of the 10.4 m telescopes of the interferometer. The spectrometer covered 90% and 66% of the integrated CO emission in the northern and southern field, respectively. Calibration and data reduction procedures were similar to those described in Lo *et al.* (1987).

III. RESULTS

Figure 1 shows a map of the CO integrated intensity of the central 2′ × 1′ (N-S by E-W) of M51 superposed on a $\lambda = 6$ cm radio continuum map kindly provided by Dr. P. Crane. It shows the excellent correspondence of the CO emission with the radio continuum ridges which are the most unambiguous

[1] Currently at the Space Sciences Laboratory, University of California, Berkeley.

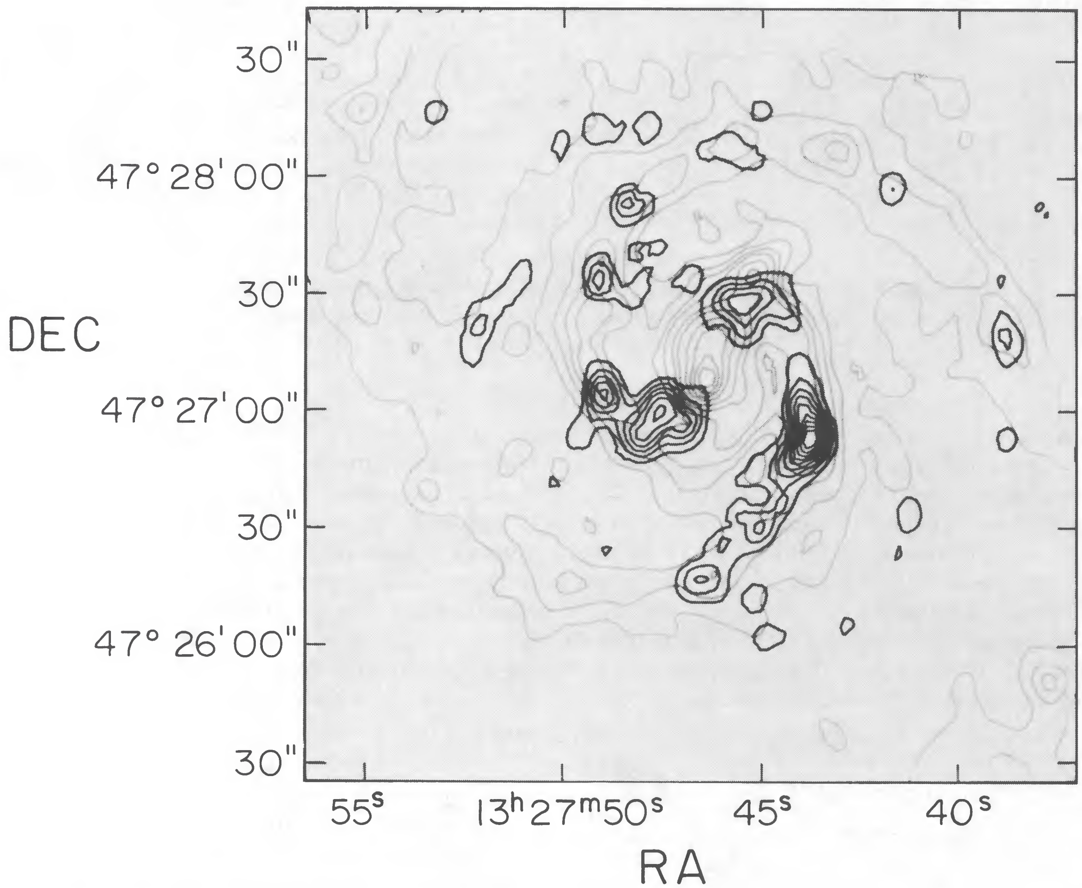

FIG. 1.—A combined integrated CO intensity map covering the inner 2′ × 1′ of M51 (*dark contours*) is superposed on a λ6 cm radio continuum map at 7″ resolution (*gray contours*; P. Crane, private communication). The contour levels of the CO emission are multiples of 9.6 K km s^{-1}.

tracer of the shock regions associated with spiral density waves (Mathewson, van der Kruit, and Brouw 1972). The absolute and relative positional accuracy is ≤ 1″. Some of the CO emission forms a coherent structure as long as 3 kpc.

The molecular spiral structure is further demonstrated in Figure 2 (Plate L2) which depicts the integrated CO emission superposed on a short-exposure plate of the inner region of M51 showing clearly the dust lanes. The relative registration is accurate to better than 3″, limited largely by the relative scaling of the CO map and the photographic print. Some of the contours in the interarm regions, especially on the periphery of the CO map, may be artifacts due to imperfect cleaning. A prominent feature of Figure 2 is that the CO emission is largely confined to the dusty spiral arms.

$\langle T_b \rangle_{300\,pc}$, the Rayleigh-Jeans brightness temperature averaged over 300 pc (corresponding to the synthesized beam; cf. Lo *et al.* 1987), of the CO emission evident on the synthesis maps ranges between 1.6 K and 4 K, averaged over 10.4 km s^{-1}. The detected emission is generally resolved, indicating size scales of at least 300 pc, much larger than that of individual giant molecular clouds (GMC) in our Galaxy (Solomon and Sanders 1980; Sanders, Scoville, and Solomon 1985).

The channel maps contain only a fraction (≤ 0.3) of the CO flux density measured from the 65″ beam of the 10.4 m telescope. As the accuracy of the single-dish and interferometer measurements of the flux density is 3 Jy and 1 Jy, respectively, the missing CO flux (6–14 Jy) cannot be due to measurement errors. *This missing flux must be mostly distributed outside the spiral arms*; otherwise, the CO surface brightness of the arms would be > 3 times higher than what is observed, much more than that allowed by the calibration uncertainty. This deduction is also consistent with the ~ 20% contrast ratio between the arm-to-interarm integrated CO intensities observed in M51 with a 33″ beam (Rydbeck *et al.*).

The detection limit of the channel maps is ~ 0.6 K (0.25 Jy per beam), so that if the undetected CO emission has the same size scales as the detected emission, $\langle T_b \rangle_{300\,pc} \leq 0.6$ K and this emission has to arise from 24 to 56 synthesized beam areas. Alternatively, as the interferometer is insensitive to structures ≥ 40″, the missing CO emission could have a surface brightness in the range: $0.3\ K \leq \langle T_b \rangle_{300\,pc} \leq 0.9$ K. The lower limit corresponds to the missing flux distributed uniformly in the 65″ primary beam, and the upper limit corresponds to the flux distributed over 40″. Since the interarm spacings in the inner part of M51 are ≤ 30″, the missing CO flux must in any case be distributed fairly uniformly in the interarm regions.

The $\langle T_b \rangle_{300\,pc}$ upper limits are too high to exclude GMC in the interarm regions, but the $\langle T_b \rangle_{300\,pc}$ of this interarm gas

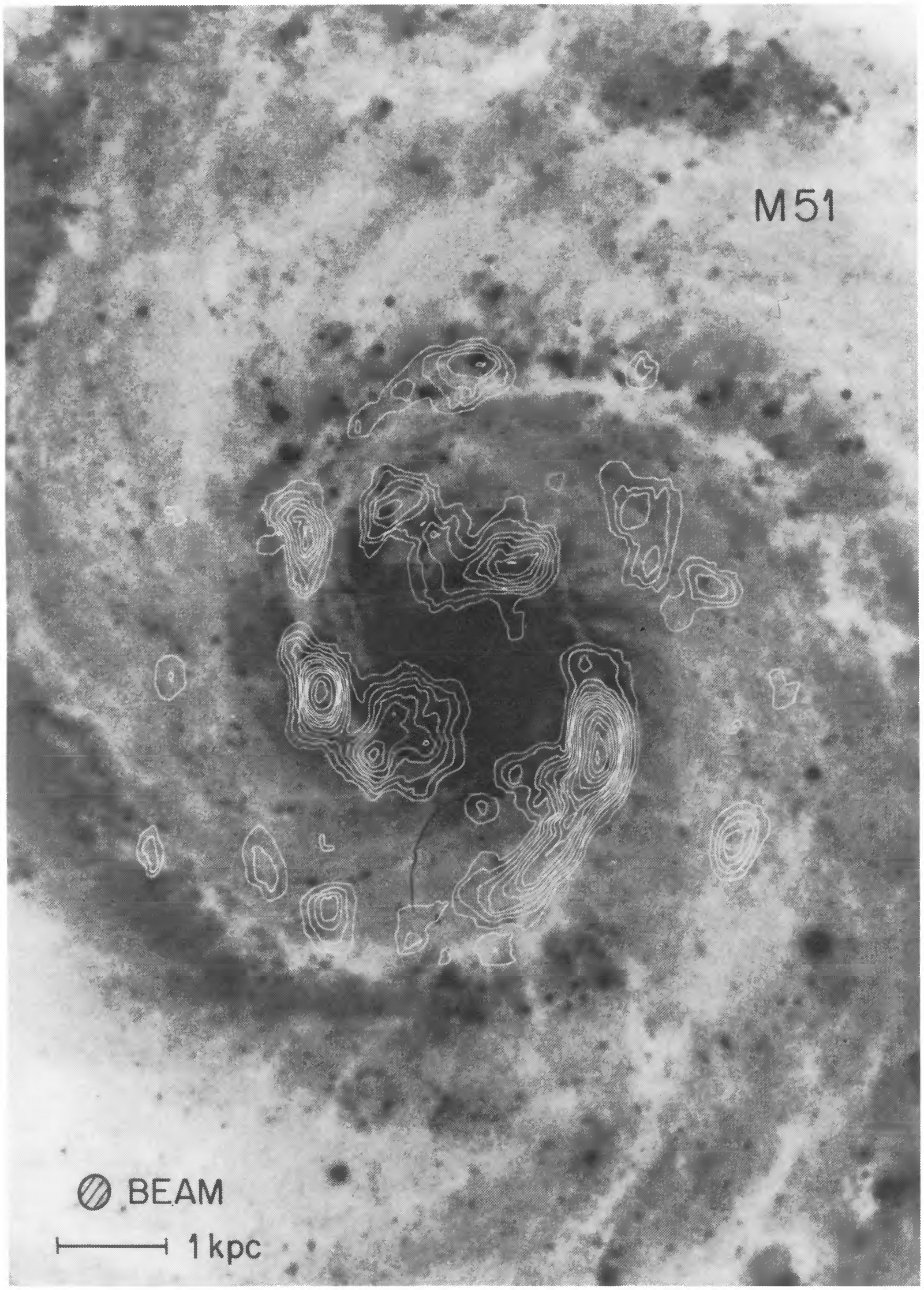

FIG. 2.—The integrated CO intensity map is superposed on a print of a short-exposure plate of the central region of M51 (J. Bedke, private communication). This CO map is different from that in Fig. 1 due to the differences in the image processing. Principally, a lower threshold on the channel maps was used in summing the maps, so that while more of the CO emission appears than in the map in Fig. 1, some of the features in the interarm regions may not be real.

LO *et al.* (*see* **317**, L64)

is more than a factor of 2 lower than that of the spiral arm gas. If the molecular gas inside and outside the spiral arms has the same velocity dispersion and the gas column density, $N(H_2)$, is proportional to the integrated CO intensity, I_{CO}, then we can infer that the arm-to-interarm $N(H_2)$ contrast ratio is at least 3 and could be as high as 15. The mean $N(H_2)$ in the observed arms in our maps is 2×10^{22} cm^{-2} or 337 $M_\odot$ pc^{-2}, higher than the typical value through individual GMC, ~ 200 $M_\odot$ pc^{-2}, using the same value for $I_{CO}/N(H_2)$ (Sanders, Solomon, and Scoville 1984).

The most intense CO emission arises from the arms close to the nucleus, but there is a minimum of CO emission from the central 600 pc of M51. This is unexpected since low-resolution single-telescope observations suggest exponential radial distribution of integrated CO intensity in late-type spiral galaxies, including M51 (cf. Young 1985; Scoville and Young 1983). The channel maps place upper limits in the central 600 pc of M51 of $N(H_2) \leq 8.7 \times 10^{21}$ cm^{-2} and $M(H_2) \leq 4.7 \times 10^7$ $M_\odot$, if the I_{CO}/H_2 conversion factor of Sanders, Solomon, and Scoville (1984) and a velocity width of 114 km s^{-1} are adopted (Rydbeck *et al.*).

As not all the CO emission is covered by the spectrometer, the velocity field cannot be reliably obtained. However, the orientation of the isovelocity contours of the CO emission observed show unambiguous deviation from those of an inclined disk of differential circular rotation. Noncircular motion has also been noted in the ionized gas by Tully (1974) and Goad, de Veny, and Goad (1979) and in the molecular gas by Rydbeck *et al.* The origin of such distortion is not clear at present, but could be due to a nonaxisymmetric nuclear gravitational potential. The velocity dispersion of the detected CO emission is < 10 km s^{-1}.

IV. DISCUSSION

a) *Molecular Cloud Complexes and Star Formation Confined to Spiral Arms*

Because of the large size-scales of the CO emission in the inner spiral arms of M51, the molecular gas distribution is probably more appropriately identified as complexes of molecular clouds. The $\langle T_b \rangle_{300\,\mathrm{pc}}$ of the spiral arm gas is higher than that of the interarm gas. Besides a higher column density, this is likely to be also due to higher gas temperature in the arms since there is evidence of recent star formation in the inner spiral arms (Telesco, Decher, and Gatley 1986; Lester, Harvey, and Joy 1986). If the volume filling factor of molecular clouds in the arms is 0.05, 5 times that in the Galaxy (Sanders, Scoville, and Solomon 1985), then the kinetic temperature of the gas is at least 15 to 33 K, similar to the warm cloud cores in our Galaxy (Solomon, Sanders, and Rivolo 1985).

The distribution of molecular gas in the inner region of M51 may be similar to that in our Galaxy. Solomon, Sanders, and Rivolo (1985) pointed out that the molecular cloud cores in the Galaxy appear to form two components, separable according to temperature: (1) a warm component closely associated with radio H II regions and more confined to (presumably) spiral arms, and (2) a more uniformly distributed cold component. In the case of M51, the spiral arm gas may be identified as cloud complexes, on a scale much bigger than the clustering scale of warm cloud-cores in the Galaxy (Rivolo, Solomon, and Sanders 1986).

The concentration of molecular gas in the inner spiral arms of M51 may be the prerequisite for the enhanced star formation there. Whether the star formation in the molecular clouds gathered in the spiral arms is due simply to gravitational instability or to triggering of cloud collapse by the large-scale shocks cannot be resolved by the present observations. In any case, the formation of the cloud complexes and the subsequent collapse to form stars must all take place within a few $\times 10^7$ yr upon entering the spiral arm.

b) *Formation and Lifetime of Spiral Arm Molecular Cloud Complexes*

The observations of large-scale molecular structure confined to the inner arms of M51 and a relatively uniform distribution of molecular clouds in the interarm would support the following picture. Cloud complexes form from the "coalescence" of molecular clouds in the presence of a spiral gravitational potential (Cowie 1981; Kwan and Valdes 1983). The complexes are redispersed into molecular clouds upon leaving the spiral arms, probably by the young star clusters formed in the arms, which can take place in $\sim 10^7$ yr (Blitz and Shu 1980; Bruhweiler *et al.* 1980; Lo *et al.* 1987). On the other hand, Roberts and Stewart (1987) have recently suggested that the formation of cloud complexes in the spiral arms is mainly due to the "orbit-crowding" of the clouds, while the disruption of complexes is explainable by the natural tendency of the cloud orbits to disperse once they leave the arm. Further observations are needed to identify the detailed processes involved.

Allen, Atherton, and Tilanus (1986) observed in M83 that H I is closely associated with Hβ emission while both the atomic and ionized gas are spatially offset from the dust lanes. They have suggested that molecular clouds are destroyed by photodissociation on a kpc scale in M83, as well as in M51 (Tilanus and Allen 1986). The results here indicate that in M51 the H_2 dissociation cannot be complete, since molecular clouds exist in the interarm regions. Furthermore, the peak H I column density observed is $\sim 9 \times 10^{20}$ H cm^{-2} (Tilanus and Allen 1986), whereas the molecular column density in the arms is $\geq 1.4 \times 10^{22}$ H cm^{-2}, more than a factor of 16 larger. The difference in the resolution may reduce the discrepancy by a factor of 5, at best. This discrepancy in the H I and H_2 column densities also places constraints on any model of forming giant molecular clouds directly from H I cloud complexes (Blitz and Shu 1980).

The molecular clouds distributed in the interarm regions would have to last long enough to reenter the next arm, unless they are somehow destroyed and reformed in the interarm regions. The time scales involved depend on the pattern speed, Ω_p, which we estimate by setting the radius of the visible galaxy equal to the corotation radius (Tully 1974; Roberts, Roberts, and Shu 1975), yielding $\Omega_p = 37.5$ km s^{-1} kpc^{-1}. This should give a reasonable lower limit to the pattern speed. As an alternative which will be close to an upper limit on Ω_p, one can set the edge of the visible disk equal to the outer Lindblad resonance, and from the rotation curves given in Goad *et al.*, calculate $\Omega_p = 71$ km s^{-1} kpc^{-1} (Lin and Shu 1967; Lin and Bertin 1985). Smaller pattern speeds reduce the time scales.

If we take the spiral arms as defined by the radio continuum ridge (Fig. 1) and the two plausible limits on Ω_p above, we estimate that the arm-crossing time is $\leq 5 \times 10^7$ yr. This time could be as short as 1.5×10^7 yr at 30″ (1.3 kpc) from the center. The effect of the shocks on the gas streamlines has been taken into account roughly by correcting the arm-crossing speed by the ratio of the mean gas surface density to the actual gas density (Shu, Milione, and Roberts 1973). The interarm crossing time is only slightly larger than the arm-crossing time close to the center, but could be as much as 1.0×10^8 yr at 45″ (2.2 kpc) from the center. Thus, the lifetime of molecular clouds in the inner parts of M51 is at least $\sim 10^8$ yr, still posing a problem of cloud support (e.g., Blitz and Shu 1980).

c) Gravitational Alignment of Molecular Cloud Complexes

Figure 1 shows that some of the CO emission forms a coherent structure ~ 3 kpc in length. High-resolution CO observations have revealed similar large-scale molecular structures in other late-tpe spiral galaxies, e.g., molecular bars in the nuclear regions of IC 342 (Lo *et al.* 1984) and of NGC 6946 (Ball *et al.* 1985). The existence of coherent structures on so large a scale (2–3 kpc) requires the action of a dynamical process, namely the gravitational response of the gas to the underlying mass distribution in the galaxy, in combination with hydrodynamical effects. In both IC 342 and NGC 6946, there is good alignment of the nonaxisymmetric nuclear bulges with the molecular bars (Lo *et al.* 1984; Ball *et al.* 1985; Zaritsky and Lo 1986). In M51, the CO emission is well correlated with the radio continuum ridge outlining the shock regions of a spiral density wave (Mathewson, van der Kruit, and Brouw 1972; Roberts 1969).

d) Central Void of H_2

The central 600 pc of M51 could still contain $\sim 5 \times 10^7$ $M_\odot$ of H_2 which would have to be somewhat cool. If the central H_2 surface density is similar to that in our Galaxy (Sanders, Scoville, and Solomon 1985), there should be $\sim 10^8$ $M_\odot$. Figure 1 shows that the central void of CO emission is very well correlated with the radio continuum complex there. Ford *et al.* (1985) have shown that the radio complex corresponds to two shock-excited, large-scale expanding bubbles on either side of the nucleus. The molecular gas may have been swept up by the expanding bubbles. The gas just outside the central void, if expelled from the center, amounts to a few $\times 10^7$ $M_\odot$. The relative minimum of H_2 in the center is unlikely to be due to photodissociation, since the H I column density at the center is $< 2 \times 10^{20}$ cm^{-2}, more than 100 times smaller than expected.

V. SUMMARY

The present observations provide the first *direct* observation of molecular spiral structure in the inner parts of M51. However, a fairly uniform distribution of molecular clouds in the interarm regions is also implied. The observations suggest the "coalescence" of molecular clouds to form cloud complexes in the presence of a spiral gravitational potential and redispersal of the complexes upon leaving the arms. The spiral-arm cloud complex phase, during which star formation may be enhanced, lasts $\leq 5 \times 10^7$ yr, whereas the lifetime of molecular clouds is at least $\sim 10^8$ yr. The spiral molecular structure thus emphasizes the importance of the underlying galactic mass distribution in determining the distribution of molecular clouds and regions of enhanced star formation.

We thank all the staff at Owens Valley who built the interferometer and made this research possible. The SIS junctions so essential to the successful operation of the interferometer were fabricated by R. Miller of AT&T Bell Labs. We are also grateful to J. Bedke of the Mount Wilson and Las Campanas Observatories for providing excellent prints of M51 used in Figure 2 and Dr. P. Crane for sending the radio continuum map. We also thank Drs. F. Shu and P. Solomon for useful discussions. This research is supported by the NSF under AST84-12473.

REFERENCES

Allen, R. J., Atherton, P. D., and Tilanus, R. P. J. 1986, *Nature*, **319**, 296.
Ball, R. B., Sargent, A. I., Scoville, N., Lo, K. Y., and Scott, S. L. 1985, *Ap. J. (Letters)*, **298**, L21.
Blitz, L., and Shu, F. H. 1980, *Ap. J.*, **238**, 148.
Bruhweiler, F. C., *et al.* 1980, *Ap. J. (Letters)*, **238**, L27.
Dame, T. M., Elmegreen, B., Cohen, R. S., and Thaddeus, P. 1986, *Ap. J.*, **305**, 892.
Cowie, L. L. 1981, *Ap. J.*, **245**, 66.
Ford, H. C., *et al.* 1985, *Ap. J.*, **266**, 298.
Goad, J., de Veny, J., and Goad, L. 1979, *Ap. J. Suppl.*, **39**, 349.
Kwan, J., and Valdes, F. 1983, *Ap. J.*, **271**, 604.
Lester, D., Harvey, P., and Joy, M. 1986, *Ap. J.*, **302**, 280.
Lin, C. C., and Bertin, G. 1985, in *IAU Symposium 106, The Milky Way*, ed. H. van Woerden, R. J. Allen, and W. B. Burton (Dordrecht: Reidel), p. 513.
Lin, C. C., and Shu, F. H. 1967, in *IAU Symposium 31, Radio Astronomy and the Galactic System*, ed. H. van Woerden (London: Academic), p. 313.
Lo, K. Y., *et al.* 1984, *Ap. J. (Letters)*, **282**, L59.
Lo, K. Y., *et al.* 1987, *Ap. J.*, **312**, 574.
Masson, C. R., *et al.* 1985, in *URSI Symposium on Millimeter and Submillimeter Wave Astronomy*, ed. J. Gomez-Gonzales (Granada: URSI), p. 65.
Mathewson, D. S., van der Kruit, P. C., and Brouw, W. N. 1972, *Astr. Ap.*, **17**, 468.
Rickard, L. J, and Palmer, P. 1981, *Astr. Ap.*, **102**, L13.
Rivolo, A. R., Solomon, P. M., and Sanders, D. B. 1986, *Ap. J. (Letters)*, **301**, L19.
Roberts, W. W. 1969, *Ap. J.*, **158**, 123.
Roberts, W. W., Roberts, M. S., and Shu, F. H. 1975, *Ap. J.*, **196**, 381.
Roberts, W. W., and Stewart, G. R. 1987, *Ap. J.*, **314**, 10.
Rose, J. A., and Searle, L. 1982, *Ap. J.*, **253**, 556.
Rydbeck, G., Hjalmarson, A., and Rydbeck, O. E. H. 1985, *Astr. Ap.*, **144**, 282.
Sanders, D. B., Scoville, N. Z., and Solomon, P. M. 1985, *Ap. J.*, **289**, 373.
Sanders, D. B., Solomon, P. M., and Scoville, N. Z. 1984, *Ap. J.*, **276**, 182.
Scoville, N., and Young, J. 1983, *Ap. J.*, **265**, 148.
Shu, F. H., Milione, V., and Roberts, W. W. 1973, *Ap. J.*, **183**, 819.
Solomon, P. M., and Sanders, D. B. 1980, in *The Third Gregynog Symposium: Giant Molecular Clouds in the Galaxy*, ed. P. M. Solomon and M. Edmunds (Oxford: Pergamon Press), p. 41.
Solomon, P. M., Sanders, D. B., and Rivolo, A. R. 1985, *Ap. J. (Letters)*, **292**, L19.

Stark, A. A. 1985, in *IAU Symposium 106, The Milky Way Galaxy*, ed. H. van Woerden, R. J. Aller, and W. B. Burton (Dordrecht: Reidel), p. 445.
Telesco, C. M., Decher, R., and Gatley, I. 1986, *Ap. J.*, **302**, 632.
Tilanus, R. P. J., and Allen, R. J. 1986, in *Proc. of Star Formation in Galaxies*, ed. C. Persson, in press.
Toomre, A., and Toomre, J. 1972, *Ap. J.*, **178**, 623.
Tully, R. B., 1974, *Ap. J. Suppl.*, **27**, 437.
Young, J. 1985, in *IAU Symposium 115, Star Formation Regions*, ed. J. Jugaku (Dordrecht: Reidel), p. 557.
Zaritsky, D., and Lo, K. Y. *Ap. J.*, **303**, 66.

R. BALL: Space Sciences Laboratory, University of California, Berkeley, CA 94720

K. Y. LO: Department of Astronomy, 1011 West Springfield Avenue, University of Illinois, Urbana, IL 61801

C. R. MASSON, T. G. PHILLIPS, S. SCOTT, and D. P. WOODY: Owens Valley Radio Observatory, California Institute of Technology, Pasadena, CA 91125