MOLECULAR GAS IN THE STARBURST NUCLEUS OF M82

K. Y. Lo

California Institute of Technology
Pasadena, California

ABSTRACT. 7″-resolution CO(1-0) observations of the central 1 kpc of M82 have resolved 2 components of molecular gas: (1) A high concentration in the central 700 pc × 200 pc, and (2) extended features that may be gas expelled from the central concentration. The central concentration of molecular gas falls in the same confines as the other tracers of recent star formation, and may be identified directly with the star-burst region.

The molecular gas in the star-burst nucleus of M82 appears to be highly disturbed and has high kinetic temperature (> 40 K), likely consequences of the high density of young star clusters. Stellar winds and subsequent supernovae from the star clusters can effectively sweep up the interstellar medium. The flux of the stellar radiation throughout the M82 star-burst region ($\sim 10^5$ $L_\odot/pc^2$) is comparable to that in Orion, at ~ 0.25 pc from the Trapezium stars, and can heat the gas to high temperature. The $N(H_2)/I_{CO}$ ratio is ~ 10 times smaller than that for the galactic GMC, but indicates a substantial column density still—$N(H_2) \geq 3 \times 10^{22}$ cm^{-2} or ≥ 500 $M_\odot/pc^2$. L_{IR}/M_{H_2} for the M82 star-burst region is 170 $L_\odot/M_\odot$, much higher than the ratio for the extended molecular disks of nearby galaxies (~ 5 $L_\odot/M_\odot$).

The spatial distribution and kinematics of the nuclear concentration of the molecular gas, as well as the 2 μm light distribution, suggest the presence of a stellar bar in M82. While accretion from outside the galaxy could have contributed to the gas supply in the nuclear region of M82, the immediate mechanisms for both supplying and confining the gas in the central 1 kpc, and for triggering the star formation may have been provided by the stellar bar.

Comparisons of the M82 star-burst nucleus to a sample of IR luminous galaxies suggest that star-burst regions in general may have a higher gas temperature (therefore higher integrated CO intensity) and much higher L_{IR}/M_{H_2} than the galactic disk, and that *L_{IR} of the star-burst regions may be essentially proportional to their area.*

1. INTRODUCTION

M82, at a distance of 3.25 Mpc, serves a prototypical system for studying the star-burst phenomenon. The most persuasive explanation for the 3×10^{10} $L_\odot$ infra-red luminosity (Telesco and Harper 1980) is that it is due to a recent burst of star formation that started $\sim 5 \times 10^7$ years ago with an exponential decay time of $\sim 2 \times 10^7$ years and produced primarily massive stars at high efficiency (Rieke et al 1980). Detailed optical studies show that very young star clusters exist in the nucleus of M82 (O'Connell and Mangano 1978, hereafter OM), and high resolution radio maps of M82 show the presence of >40 compact radio sources which are most likely young supernova remnants (Kronberg et al 1985). Thus, star-bursts in the nucleus of M82 seem well founded.

Extremely large infra-red luminosity is observed towards the central few hundred pc to kpc scale in many galaxies (cf. Telesco and Harper 1980). Recent IRAS observations have shown that galaxies with extremely large far-IR luminosity are fairly common (Soifer et al 1986). While star-bursts could be the natural explanation for the luminosity, the underlying mechanisms for star-bursts are not well understood. Questions concerning (i) the source of the molecular gas, the raw material for star formation, (ii) the mechanisms for collecting the gas in the star-burst regions, typically the central kpc, and (iii) the triggering of star-bursts need to be answered. In addition, some mechanism to regulate the runaway star formation may be required.

One of the most useful approaches to this problem is through an investigation of the molecular gas, the raw material for forming new stars, using observations of the relatively abundant trace molecule, CO. M82 is the brightest emitter of the CO radiation which has been studied extensively via single telescopes (Rickard et al 1977; Knapp et al 1980; Olofsson and Rydbeck 1984; Young and Scoville 1984; Nakai 1984). Even at the modest distance of M82, single telescope CO observations have rather poor linear resolution: a few hundred pc at best (e.g. Nakai 1984). With the Owens Valley millimeter-wave interferometer, we have observed the molecular gas distribution within the central $\sim$ 1 kpc region with a linear resolution of 110 pc, adequate to resolve spatially some of the prominent irregular dusty filaments visible in optical pictures.

In this paper, we present high resolution interferometric observations of the CO(1-0) emission from the central $\sim$ 1' region of M82. (For details, see Lo et al 1986.) They show that the molecular gas can be divided into 2 components: (1) a high concentration in the central 700 pc × 200 pc, and (2) extended regions that may be shell-like and filamentary in structure. We also discuss the properties of the interstellar medium in the nuclear region of M82 implied by our and related observations and the implications of our observations for star formation in M82 and in other galaxies.

2.   NUCLEAR CONCENTRATION OF MOLECULAR GAS

2.1   Relationship to Star-burst Region

Figure 1 shows the integrated CO intensity map of the central $\sim$1' of M82 superposed on a print of an 103aO plate of the galaxy. The CO source, 1.5 kpc by 0.3 kpc in extent, is roughly aligned with the disk of the galaxy and shows two prominent peaks $\sim$ 25" ($\sim$ 450 pc) apart, with a weaker one in between. To illustrate the relative distribution of the molecular gas and other components in the nucleus of M82, we have superposed the integrated CO intensity maps on (i) a λ6 cm map, (ii) a 10 μm map and (iii) a 2.2 μm map of the nuclear region of M82 (figure 2;cf. Rieke et al 1980). Both the 6 cm and 10 μm emissions trace the locations of recent formation of massive stars within a region of $\sim$ 700 pc × 200 pc. Figure 2 shows that the region of recent star formation falls in the same confines as the central concentration of the CO distribution. However, the correspondence is not exact in detail.

The correlation of strong CO emission and recent star formation is further illustrated by figure 3 in which a 0."15-resolution λ 6 cm map (Kronberg et al 1985) is superposed on the integrated CO intensity map. The general 6 cm distribution is very well correlated spatially with the central concentration of CO emission. There are many compact radio sources in the 6 cm map, lying preferentially on the periphery of the overall 6 cm distribution (with the majority to the south). These compact sources are most likely supernova remnants, some of which have been observed to be decreasing in flux and must be quite young (Kronberg and Sramek 1985). However, the supernova remnants appear to be offset from peaks of the CO emission.
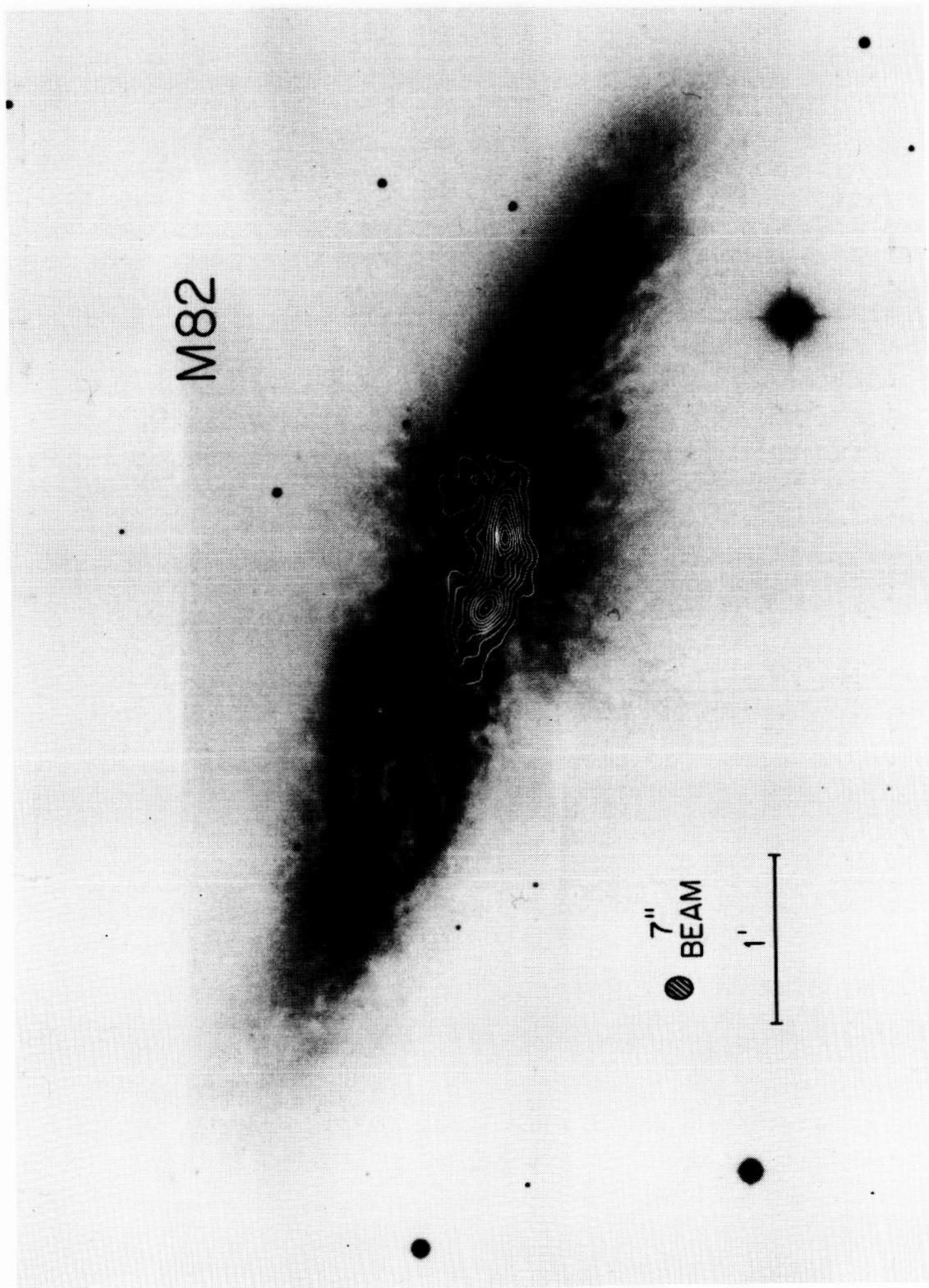
Figure 1: The integrated CO intensity map of the central 1' of M82 at 7" resolution is superposed on a copy of a 103aO plate taken with the Hale 5m telescope. This map made from the broadband channel emphasizes the large velocity dispersion emission and some of the more extended small velocity dispersion emission may be below the sensitivity of this map. The contours are multiples of 187.5 K-km s^{-1}.
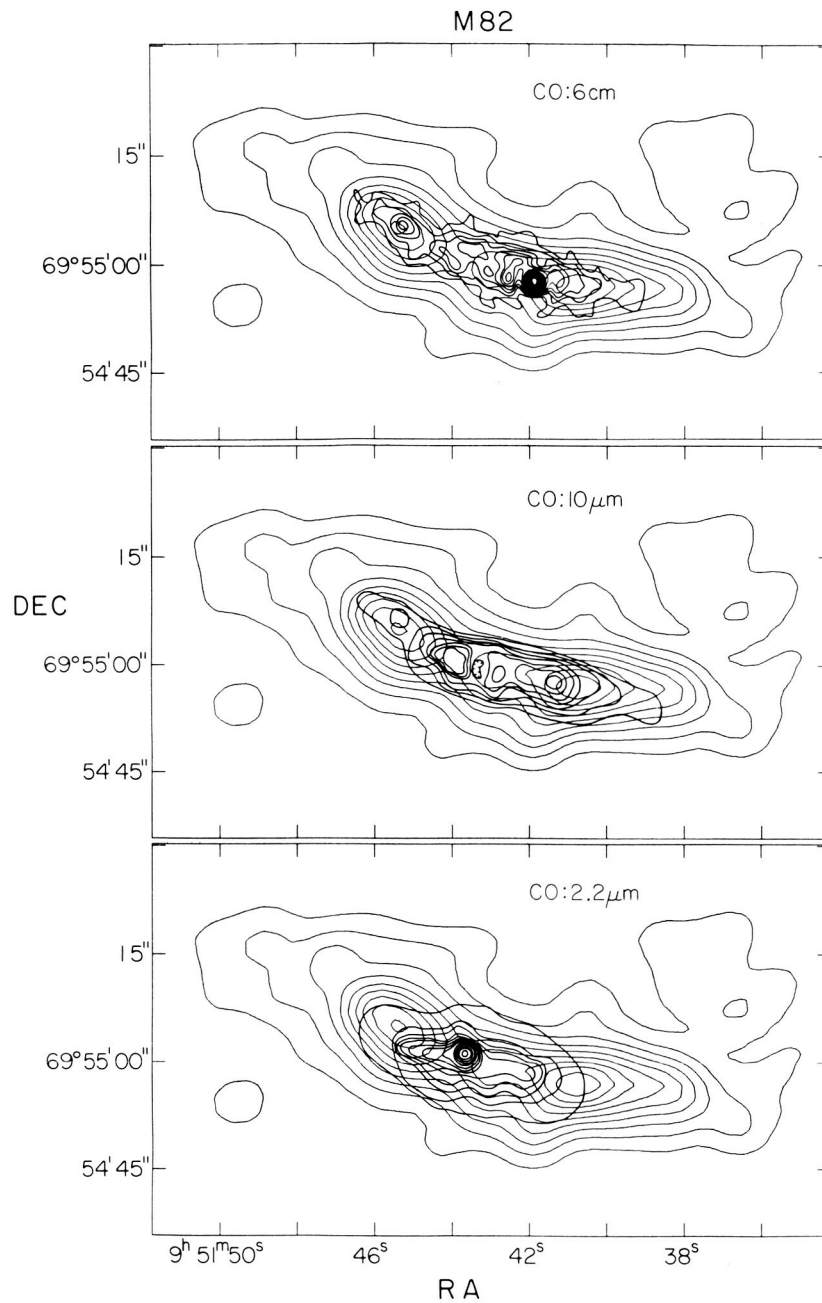
M82

CO:6cm

CO:10μm

DEC

CO:2.2μm

RA

Figure 2: Comparisons of the integrated CO intensity map to λ 6 cm radio continuum (top), 10μm emission (middle), both tracers of recently formed stars, and 2.2 μm emission (bottom), presumably the underlying stellar nucleus and disk (Rieke et al 1980). Note that the CO peaks are not symmetrically placed about the 2.2 μm nucleus. The accuracy of the positional registration for all the maps is ≤ 1″.
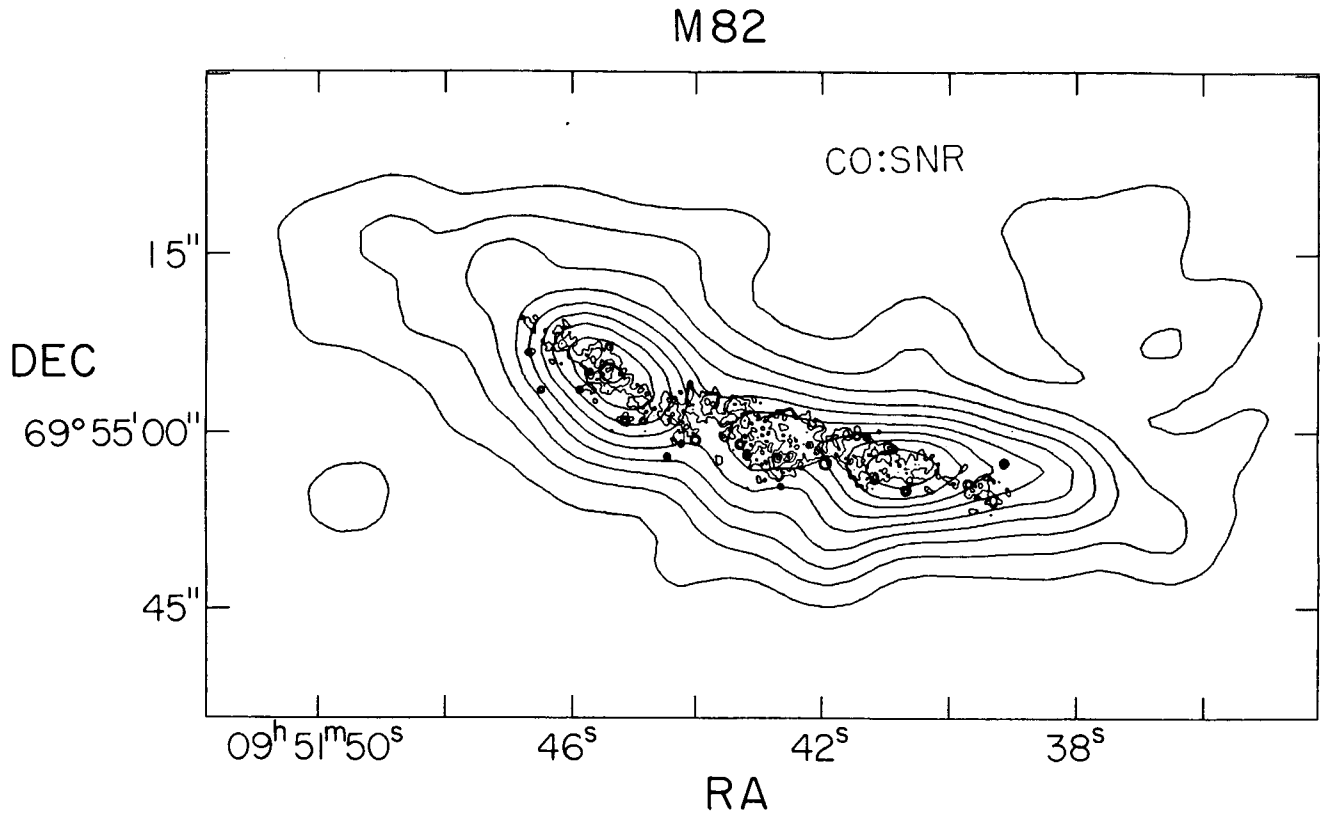
M82

Figure 3: A 0.″15 resolution λ 6 cm radio continuum VLA map of M82 (Kronberg et al 1985), showing the discrete radio supernova remnants, is superimposed on the integrated CO intensity map. Note that the remnants are **not** situated on the CO intensity peaks.

2.2 Kinematics

From the available channel maps, an intensity-weighted velocity field of the CO emission measured with the spectrometer can be constructed, as shown in figure 4. The overall velocity gradient suggests a general rotation of the gas. The rotation axis would be at a PA of $\sim 130°$, about 20° offset from the stellar minor axis of M82. It appears that the kinematic and structural major axes of the CO emission are not aligned. Similar misalignment is observed in the velocity field derived from optical emission lines (Heckathorn 1972; OM; Williams et al 1985). Thus, the observed gas motion cannot simply be that of an inclined circularly rotating ring or disk. Within the central 300 pc region, the high brightness CO emission in the nucleus has a constant velocity gradient of 0.7 km s^{-1}/pc, compared to the Hα velocity gradient of ~ 0.9 km s^{-1}/pc within the central 180 pc (OM). The velocity gradient of the HI gas within the central 500 pc is ~ 0.5 km s^{-1}/pc (Weliachew et al 1984). The orbital time scale of the neutral and ionized gas within the central 500 pc of M82 is $\leq 10^7$ yr.
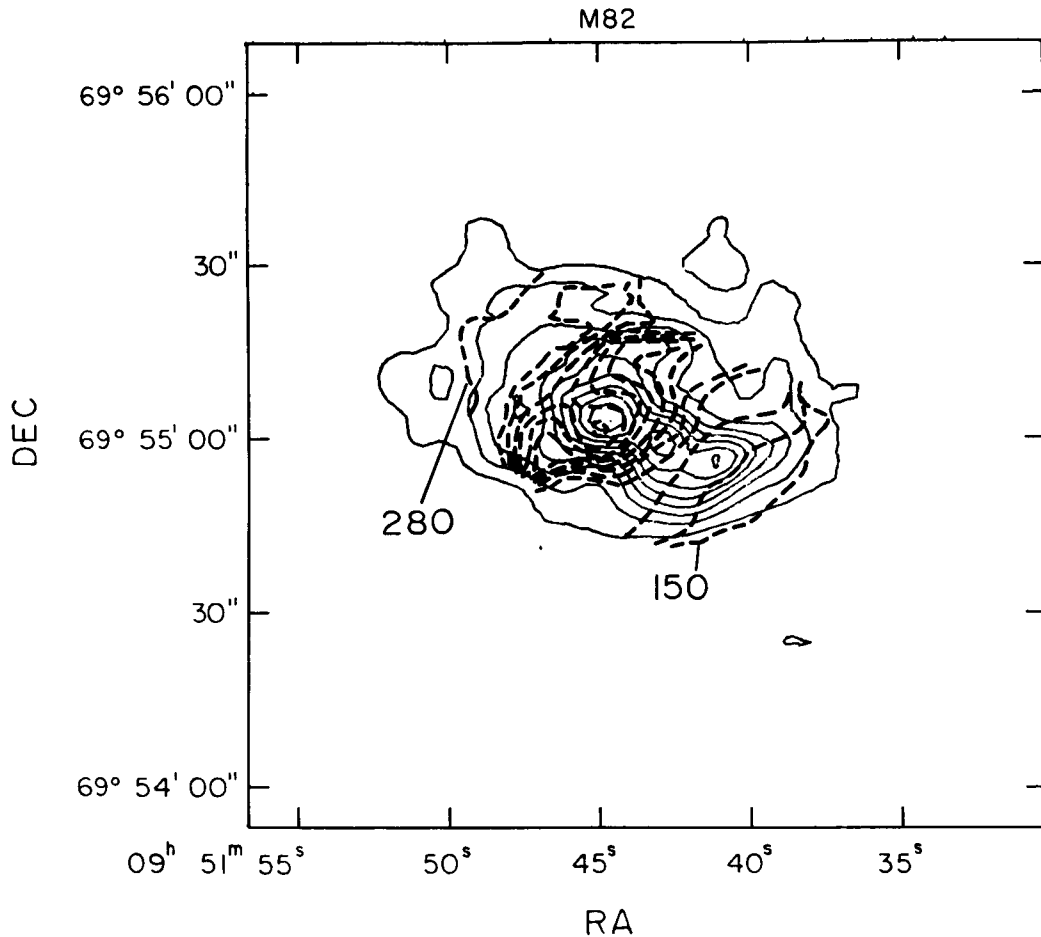
Figure 4: The dashed lines are the isovelocity contours at 10 km s^{-1} intervals, showing the velocity field of the CO emission falling within the spectrometer. The numbers are the LSR velocities in km s^{-1}. The solid contours show the CO intensity map obtained from summing all the emission in the observed channel maps and therefore does not represent all the emission in the central 1'. The contours of the solid lines are multiples of 54 Jy-km s^{-1}/beam.

3. EXTENDED EMISSION: MOLECULAR SUPERSHELLS ?

The channel maps (figure 5) show a bright, slightly resolved component as well as fainter extended emission. The bright component is CO emission from the central concentration, distinguishable from the extended emission by its higher brightness temperature and confinement. In many of the maps, the extended CO emission appears to show arc-like structures. As the linear resolution of the beam is ~ 110 pc, any distinctly resolved feature would have a scale > 200 pc. The arc-like structures at $V_{LSR} = 234.6$ km s^{-1} have scale size up to 400 pc. At other velocities, the extended emission may show overlapping arc-like structures, and sometimes, the structure retains some similarities over 2 to 3 channel maps (see, for example, $V_{LSR} = 286.2$, 297.0 and 307.4 km s^{-1} in figure 5.)
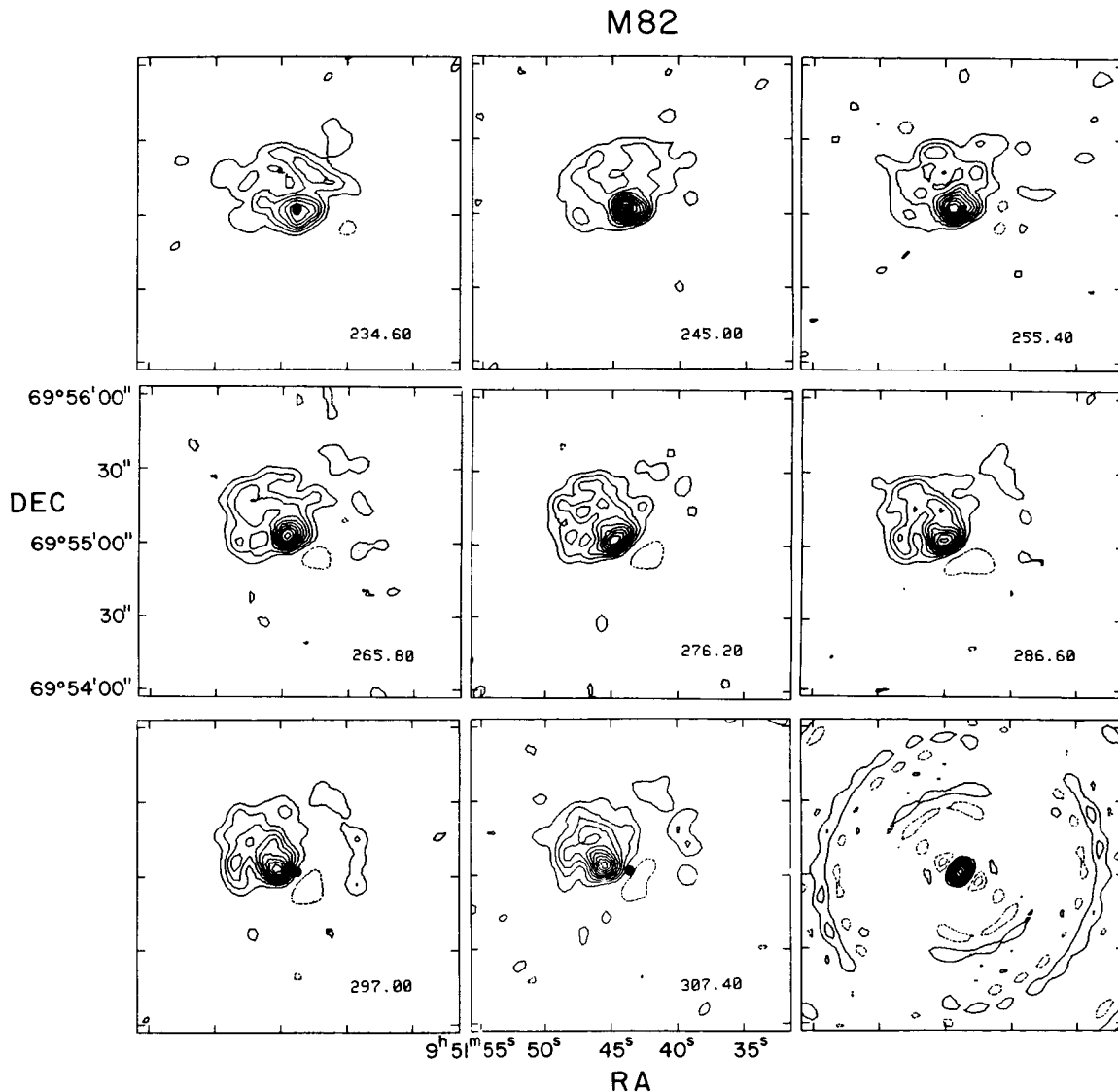
Figure 5: The "cleaned" 10.4 km s^{-1} channel maps all show the presence of a bright component and an extended fainter component (< 0.5 of peak brightness) which shows arc-like structures. The black dot denotes the 2.2 μm peak (cf. figure 2). The numbers refer to the V_{LSR} in km s^{-1} at the center of the 10.4 km s^{-1} channels. The shift in position of the emission relative to the 2 μm peak indicates a general velocity gradient. The contours are multiples of 0.7 Jy/beam or Rayleigh-Jeans brightness temperature of 1.1 K.

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The total flux density from the extended emission is roughly twice that of the central concentration in each of the channels. This implies that the molecular gas mass involved in the extended emission is roughly twice that in the central concentration, if the same conversion factor from I_{CO} to H_2 column density applies to both. If the CO emission is optically thin (see below), then the H_2 mass in the extended emission is $\sim 10^8$ M$_\odot$.

If we identify the extended emission as largely due to gas expelled from the central concentration, perhaps in the form of incomplete shells, we may estimate the following parameters. The continuity of structure over only 2 to 3 channels may indicate that the present expansion velocity is low, ≤ 10 to 15 km s^{-1}. With scale size ranging up to ~ 400 pc, the implied dynamical time scale is on the order of 10^7 yr. The expansion kinetic energy of the extended emission can be estimated as $\sim 1/2 \times 10^8 M_\odot \times$ (10 km s^{-1})^2 or $\sim 10^{53}$ ergs.

These shell-like structures may be similar to the HI supershells first identified by Heiles (1976, 1979) in our galaxy. Similar large and energetic HI shells have been identified in M101 (Allen et al 1978) and in M31 (Brinks 1984), as well as in other galaxies (cf. McCray and Kafatos 1985). A single supernova or the stellar wind from an individual O star cannot account for the large kinetic energy and scale size of one of these supershells (cf. Heiles 1979). A supershell can be formed from sweeping up the HI medium by the combined action of the stellar winds and subsequent supernovae from an OB association (Bruhweiler et al 1980; Tomisaka et al 1980; McCray and Kafatos 1985).

Given the enhanced level of recent star formation in the M82 nucleus, it may be natural to identify the extended CO emission with supershells. As the interstellar medium in the nucleus of M82 is quite different from those in the galactic disks (e.g. much higher mean density), the formation of such supershells requires more extreme energy input. The substantial mass ($\geq 10^8$ M$_\odot$) contained in the extended emission suggests that the interstellar medium is highly disturbed.

4.   THE INTERSTELLAR MEDIUM IN THE NUCLEUS OF M82

4.1   Highly Disturbed Molecular Gas

While the gas in the nuclear concentration is only slightly resolved by the 7″ beam, its disturbed structure is suggested by a short exposure plate of M82 (cf figure 1 of OM) that shows a very patchy distribution of the obscuring dust on scales as small as $\sim 2''$. Furthermore, the close correlation of a large number of young radio supernova remnants with the CO emission also implies that the medium would be highly disturbed by the explosions (cf. figure 4). The extended CO emission is most likely due to gas expelled from the central concentration. Thus, there exist both direct and indirect indications of a highly disturbed molecular gas medium in the central 1 kpc of M82.

4.2   High Gas Temperature

The peak T_b of CO emission from the central concentration of M82 ranges between 9 to 15 K. this is much higher than the brightness temperature of the clouds in our Galactic disk when averaged over ~ 100 pc. The galactic values can be no larger than the 3 to 6 K (Sanders et al 1985; Blitz 1980). Taking into account the less than unity filling factor and probable small optical depth of the CO emission, one would infer that *the kinetic temperature of the gas in the central concentration (extent $\sim$ 700 pc) is greater than 40 K.*

Maintaining such high kinetic temperature for a substantial amount of gas over a large extent requires special circumstances. However, the nuclear region of M82 has a high space density of young massive stars (OM) and a very intense radiation field ($\sim 10^5$ $L_\odot/pc^2$ or ~ 45 ergs s^{-1} cm^{-2}, about 10^4 times that of the average galactic interstellar medium; Tielens and Hollenbach (1985)). *The molecular gas throughout the nuclear region of M82 is exposed to a radiation field not very different from that in Orion within 0.2 pc of the Trapezium stars.*

If the H_2 gas is highly disturbed by the stellar winds and supernova explosions from the young star clusters, with resultant sheet-like structures, large surface area of the molecular gas would be exposed to the intense radiation field external to the gas. Surface layers of hot molecular gas ($T_k \sim$ 100 K, thickness corresponding to $A_V \sim 2$) are obtained under such circumstances, heated primarily by photoelectric emission from dust grains (Tielens and Hollenbach 1985).

4.3 Column Density and Mass of H_2

Given the gas in the star-burst nucleus of M82 is found in very different conditions as the galactic disk GMC, the conversion from the observed integrated CO intensity to H_2 column density may be different. Since the observed properties of CO emission from the nucleus of M82 can be explained by a hot, optically thin source with a large area filling factor, the H_2 column density implied by the CO(1-0) intensity in this limit is 2.6×10^{19} I_{CO} cm^{-2} (cf. Knapp et al 1980), ~ 14 times smaller than that given by the conversion for galactic GMC (Sanders et al 1984). Also, the visual extinction implied by the CO intensity would then be consistent with that derived from other methods (Rieke et al 1980; Jaffe et al 1984). Within the central concentration (700 pc $\times$ 200 pc), the mean H_2 column density is 2.6×10^{22} cm^{-2}, or 430 $M_\odot/pc^2$ and the total H_2 mass is 6.0×10^7 $M_\odot$.

5. STAR FORMATION IN M82

5.1 Gas Supply

Detailed optical studies of M82 show that outside the central 2 kpc, the current star formation rate is abnormally low compared to normal late-type spirals (OM). In contrast, the central region has had very active star formation in the last 10^8 years, with the central star clusters being the youngest. The observations here show that a high concentration of neutral gas is found in the region of most recent star formation (central 700 pc), suggesting that a fresh supply of gas has entered the central 1 kpc to fuel the star formation during the last 10^8 years. To support the observed luminosity, massive stars must have been formed at a rate of $(L/10^{10}$ $L_\odot)$ $M_\odot$/year or ~ 3 $M_\odot$/year (e.g. Scoville et al 1985) over the last 10^8 years, requiring a mean gas supply rate of > 3 $M_\odot$/year over the same period.

It has often been suggested that tidal interaction with M81 could be responsible for the observed properties of M82. The fuel for the last burst of star formation may have been accreted during the interaction with M81. There exists $\sim 10^9$ $M_\odot$ of HI surrounding M82 (Cottrell 1977; Killian 1978).

5.2 Confinement Mechanisms

However, it is not clear how the tidal interaction confines the gas within the central kpc of M82. Furthermore, NGC253, another star-burst galaxy with properties very similar to M82 (Rieke et al 1980), is not in an interacting system, so that additional mechanisms besides tidal interaction may

be necessary. Both the spatial and kinematic distributions of the nuclear concentration of molecular gas may be consistent with the gas responding to a non-axisymmetric mass distribution in M82. 2.2 μm observations of Rieke et al (1980) and Scoville (private communications) show that the central 1' of the M82 has a different PA from the galaxy as a whole. Furthermore, the 2.2 μm intensity profile of M82 shows a plateau with a scale size of 1' in addition to an exponential profile typical of spiral galaxies. This profile is similar to those of barred spiral galaxies observed in the near-IR by Baumgart and Peterson (1986). Thus, there may be indirect indications of a stellar bar in M82, although the large inclination of the galaxy makes a definite identification difficult.

The effects of oval distortions in the nuclear bulges of spiral galaxies on the gas dynamics in the inner galaxy are significant (Huntley 1977; Zaritsky and Lo 1986), as perhaps illustrated in the high resolution observations of CO emission from nuclear regions in IC 342 (Lo et al 1984) and NGC 6946 (Ball et al 1985). An important consequence is the resulting radial transport of gas towards the center. In IC342, a few $\times$ 10^8 $M_\odot$ of gas are confined to a bar structure 1500 pc long, and the velocity field suggests the gas flow can be approximated by highly elliptical orbits. Thus, the orbital time scale of $\sim 10^7$ yr implies that on the average ≥ 10 $M_\odot$/yr of gas is brought towards the center. A similar process due to a stellar bar may have supplied the gas to the central kpc of M82.

5.3 Triggering Mechanisms ?

Do the star-bursts in M82 occur simply because a large amount of H_2 has been collected in the nuclear region, independent of external factors ? Kronberg et al (1985) identified > 40 radio supernova remnants of which the brighter (younger) ones are aligned along a quasi-linear feature ~ 650 pc $\times$ 60 pc in extent and are offset from the peaks of the CO intensity distribution (figure 3). Unless the H_2 distribution follows that of the supernova remnants when viewed at sufficiently high resolution ($\leq 3''$), it seems unlikely that the precursors of the supernova remnants - massive stars - were formed along a "line" as a result of spontaneous collapse of the molecular clouds. A large-scale external mechanism was probably involved in initiating the formation of massive stars along the quasi-linear feature in the nucleus of M82 (cf. Kronberg et al 1985).

The same underlying mechanism responsible for supplying gas to the nuclear region and for aligning the gas may also be triggering star formation in the collected gas. A stellar bar can induce shock fronts in the gas (e.g. Roberts, Huntley and van Albada, 1979) which would lead to increased cloud collisions and growth of GMC's along the shock fronts, both of which may help to accelerate cloud-collapse to form stars (Lo et al 1984). A stellar bar in M82 may have played an important role in the star-bursts.

5.4 Regulation of Star Formation ?

The current state of the H_2 medium in the nucleus of M82 appears highly disturbed as a result of the recently formed stars. Such a medium may be unsuitable for further star formation until the gas has been collected into giant molecular clouds again by some large-scale gravitational mechanisms such as the ones discussed above. Thus the star-burst could be its own limiting factor in continuing star formation, due to its disruptive effects on the interstellar medium. Sustained continuous enhanced star formation may not be possible, which could explain why the gas supply is not exhausted in all the galaxies and star-bursts are still possible at the current epoch.

6.   IMPLICATIONS FOR STAR-BURST GALAXIES

6.1   High CO Intensity from Star-burst Regions

The high gas temperature in the M82 star-burst nucleus is likely the result of the very high density of young star clusters there. It is therefore interesting to estimate the the star density within such regions of other IR luminous galaxies. We have listed in Table I a sample of IR luminous galaxies with measured IR luminosity, L_{IR}, (1 to 300 μm; Telesco and Harper 1980; Becklin et al 1980) and 10 μm size. Except for the nonthermal contribution to a fraction of the luminosity of Arp 220, NGC 6240 and NGC 1068 (Becklin et al, this conference; Wynn-Williams 1985; Telesco et al 1984), L_{IR} is predominantly due to the luminosity of young stars formed in the central regions (Telesco and Harper 1980) and the 10 μm size is a measure of the extent of the recently formed stars. Thus, if we assume that the stars are uniformly distributed in a flattened circular distribution, with extent d, given by the 10 μm size, $\Sigma = L_{IR}/\pi(d/2)^2$, the mean IR luminosity per unit area, is a measure of the stellar luminosity per unit area in the star-burst region and indirectly a measure of the surface mass density of young massive stars. Σ is within a factor of 2 of 10^5 $L_\odot/pc^2$ for all these galaxies, coresponding to a few B0 stars per square parsec (> 100 $M_\odot/$ pc^2).

The large Σ also indicates that the molecular gas throughout such star-burst regions is exposed to a high FUV radiation flux. In contrast, in an average region of the galactic disk, molecular clouds

TABLE I

LUMINOSITY AND SURFACE BRIGHTNESS
OF SOME IR-LUMINOUS GALAXIES

GALAXY	L_{IR} (L)	$d_{10\mu m}$ (pc)	Σ $(10^5 L/pc^2)$
Milky Way	2×10^9	230[a]	0.5
NGC 253............	3×10^{10}	≤ 500[b]	≥ 1.5
NGC 1068	2×10^{11}	3000[c]	0.3
NGC 2903	7×10^9	300 × 150[d]	1.6
NGC 3034 (M 82) ...	3×10^{10}	470[b]	1.5
NGC 5236 (M 83) ...	2×10^{10}	460[d]	1.2
NGC 6949	2×10^{10}	640 × 800[d]	0.4
IC 342	3×10^9	300[e]	0.4
Arp 220............	1×10^{12}	2000 × 4500[f]	1.1
NGC 6240	5×10^{11}	2500[f]	1.0

[a] Low *et al.* 1977.
[b] Telesco and Harper 1980; Jaffe *et al.* 1984.
[c] Telesco *et al.* 1984.
[d] Rieke 1976.
[e] Becklin *et al.* 1980; Telesco, private commumication.
[f] Rieke *et al.* 1985.

are located in quite different conditions (cf Draine 1978; Goldsmith and Langer 1978). Furthermore, the cosmic ray ionization rate of H_2, ζ, if proportional to the much increased supernova rate per unit area in the star-burst regions, would lead to much more significant cosmic ray heating of the molecular gas (cf. Goldsmith and Langer 1978). *Thus in star-burst regions generally, the molecular gas is likely to be heated to higher temperature, resulting in higher CO intensity, compared to a GMC in our galactic plane.* The standard $N(H_2)/I_{CO}$ ratio of the galactic GMC may not apply to star-burst regions in general. However, the amount of H_2 mass could still be high, given the generally higher I_{CO} expected from the star-burst regions.

6.2 High Star Formation Efficiency

From our observations, we can estimate a mean star formation efficiency (ϵ, the fraction of gas that has been converted to stars in the star-burst) directly for the star-burst nucleus of M82. The total amount of gas (H_2 + HI + ionized gas) within the central 1 kpc is $1.8 \times 10^8 \, M_\odot$, including the extended gas which we assume to have been expelled from the central concentration. The amount of stellar mass involved in the star-bursts is $2 \times 10^8 \, M_\odot$, indicating that ϵ is 0.5 (see also Rieke et al 1980). This efficiency is much higher than inferred for our galaxy generally (Wilking and Lada 1985), but *the physical mechanisms for such high ϵ in star-burst regions are not clearly understood.*

6.3 L_{IR} depends on Area of Star-bursts

The nearly constant Σ (Table I), if upheld in larger samples of IR luminous galaxies, may mean that a nearly constant stellar surface density is formed in star-bursts. This suggests some saturation effects in the underlying mechanisms in the star-burst process. One factor could be that there is a limit to the maximum possible surface density of H_2 in a galaxy. Tightly packing galactic GMC's in a thickness of 100 pc would yield a surface H_2 density of $\sim 500 \, M_\odot/pc^2$. Another self-regulating process could be the disruption of the interstellar medium by the recently formed massive stars, as is perhaps seen in M82.

If there are physical limits to the surface densities of young stars that can be formed in the star-burst process, then the luminosity of the star-burst region would depend strongly on its extent. For galaxies with an extreme luminosity of $\sim 10^{12} \, L_\odot$, the requisite star-burst, if limited to $\Sigma \sim 10^5 \, L_\odot/pc^2$, would take place over ~ 3.5 kpc. *This extent is much smaller than the typical galactic dimension* and subtends a very small angle for the more distant galaxies (3.5 kpc = $7''$ at 100 Mpc). Under this hypothesis, galaxies with luminosities of 10^{11} and $10^{10} \, L_\odot$ would have star-burst regions with characteristic dimensions of ~ 1 and ~ 0.3 kpc, respectively. High resolution far-IR observations are required to verify this hypothesis.

6.4 Why are the More IR Luminous Galaxies Mergers ?

The more luminous IR galaxies ($L > 10^{11} \, L_\odot$), if due to star-bursts, cannot be easily supported in isolated or loosely interacting galaxies (Lo et al 1986). In strongly interacting or merging galaxies, the twin requirements of sufficient gas supply and of triggering simultaneous star formation over a large extent are more likely to be satisfied. In such cases, strong tidal disruption of the underlying galaxies and the gas distribution could initiate star-bursts over a few kpc extent, perhaps via direct cloud collisions or as a result of concentration of large amount of gas in the same place. Thus, while the amount of gas in the merger may be only the sum of the gas in the two galaxies, *the resulting L_{IR}, if proportional to the area of interaction, can be many times higher than would be implied if the luminosity is simply*

proportional to the mass of gas present. Also, the star-burst regions in such mergers need not coincide with the nuclear regions.

7. CONCLUSIONS

The aperture synthesis CO observations of the central 1 kpc of M82 presented here provide the highest resolution probe yet achieved of the molecular gas within a star-burst nucleus. They have enabled a closer examination of the underlying processes involved.

1. The 7″ resolution observations have identified a 700 pc × 200 pc concentration of H_2 gas in the same confines as tracers of recent star formation in the nucleus of M82, amounting to 6 × 10^7 $M_\odot$. The gas temperature is very high ($T_k > 40$ K) throughout this region and is most likely due to the high stellar radiation flux there ($\sim 10^5$ $L_\odot/pc^2$, comparable to that in Orion). L_{IR}/M_{H_2} for the M82 star-burst nucleus is ≥ 170 $L_\odot/M_\odot$, reflecting very high star formation efficiency.

2. The observations have also identified extended CO emission that may be due to gas expelled from the central concentration. It suggests that the molecular gas in the nucleus of M82 is highly disturbed, most likely resulting from the stellar winds and subseqent supernovae from the OB associations formed in the star-burst. The kinetic energy involved in the extended gas is $\geq 10^{53}$ ergs. The extended emission may have structures similar to the HI supershells seen in the Galaxy and other galaxies.

3. The concentration of H_2 within the central ~ 700 pc of M82 requires an explanation. The distribution and kinematics of the central gas concentration, as well as the 2.2 μm light distribution, all suggest the presence of a stellar bar in the central region of M82. Such a bar may provide the underlying mechanisms both to transport the molecular gas towards the center and to trigger the star-burst. While tidal interaction with M81 may provide some of the gas needed for star-formation, the more direct cause of star-burst in M82 is probably provided by the stellar bar.

4. Comparisons of the nucleus of M82 to a sample of other IR luminous galaxies suggest that the flux of stellar radiation in all the star-burst regions is high and comparable in magnitude. This implies that the gas temperature (and therefore the CO intensity) in the star-burst regions may generally be higher than that found in the galactic disk. The $N(H_2)/I_{CO}$ is likely to be smaller than the galactic ratio, but the higher I_{CO} expected from such regions could indicate substantial H_2 column density still.

5. Existing evidence for a sample of 10 IR luminous galaxies suggests that the star-burst regions may have a nearly constant mean IR luminosity per unit area, possibly a result of physical limits of the surface density of young stars that can be formed in the star-burst process. This would imply that L_{IR} of luminous star-burst galaxies is primarily proportional to the area of the star-burst. Such a dependence can explain why the more luminous galaxies are mergers.

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DISCUSSION

WATSON:

Given the structure of the molecular ring in M82 and the possibility of its being a resonant orbit in a bar potential, what do you 'predict' for the parameters of the bar, i.e., size, pattern speed, etc.? Is it consistent with the wings seen on the 2μm distribution?

LO:

As M82 is so highly inclined, none of the parameters of the 'molecular ring', or of a stellar bar is well determined. So, I have not made quantitative comparisons of the parameters involved. It is suggestive, however, that the wings seen of 2μm distribution have a comparable scale to the starburst region.

MEZGER:

You quote an $N(H_2)/I_{CO}$ ratio for M82 which is about a factor of 10 smaller than the value used for our Galaxy. This would lead to an underestimate of the total mass of gas in M82. I would have expected the opposite. How did you derive this value?

LO:

The $N(H_2)/I_{CO}$ ratio I quoted was derived from the CO emission in the optically thin limit. The resulting gas column density is consistent with the 400μm observations of the dust continuum of Jaffe *et al.* (1984, *Ap.J.* **285**, L31).

THRONSON:

How do your observations compare with single-dish data in (a) total intensity and (b) line shape and structure?

LO:

At the velocities at which the interferometric observations were made, the total flux is comparable to the single dish measurements.

SHULL:

If supernova remnants are common in M82, their evolution will be speeded up and the x-rays from their hot interior will be effective at ionizing, heating and exciting large volumes of molecular gas.

Have you looked for evidence of this excitation or of enhanced star formation due to supershells?

LO:

In the starburst nucleus of M82, the observed high gas temperature is very likely due to heating by a very high far-UV radiation field, as well as by the enhanced cosmic ray flux and the x-rays, as you have mentioned. The extended CO emission within the central 1' of M82 may be naturally identified with supershells. To look for enhanced star formation within the supershells requires higher resolution ($< 2''$) observations of both the molecular gas and the far-infrared emission.

YOUNG:

If the interstellar radiation field is heating the clouds in M82, the 2-1/1-0 ^{12}CO ratio may not be probing the same regions and cannot be used to argue that the gas is optically thin. And, if the CO is optically thin, the CO is not a good tracer of the H_2 mass.

LO:

The important point is that the observed gas properties within the star-burst nucleus of M82 are very different from those in our Galactic disk, presumably the result of very different physical conditions within the M82 nucleus. The optically thin CO limit leads to a gas column density consistent with the dust opacity derived from the 400μm observations of the central $\sim$40" of M82, if the gas to dust ratio is assumed to be the same as the Galactic value (Jaffe *et al.* 1984).