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CO IN STEPHAN'S QUINTET: FIRST EVIDENCE OF MOLECULAR GAS IN THE INTRAGROUP STARBURST

YU GAO[1,2,3] AND CONG XU[1]

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ABSTRACT

We present the first interferometric evidence of CO (1–0) emission in the intragroup starburst (IGS) region of HCG 92 (Stephan's Quintet). BIMA's large primary beam fully covers both the IGS region and the dominant group member Seyfert galaxy NGC 7319, as well as partially covering the intruder galaxy NGC 7318B. CO emission of $\gtrsim 4\ \sigma$ is detected in all of them. The detection of the CO emission associated with the IGS is further supported by comparisons with observations in other wave bands (e.g., H I, mid-IR, and Hα). Assuming the standard conversion factor, (3.6–8.0) × $10^8\ M_\odot$ molecular gas is found to be associated with the IGS. By confining ourselves to the region of the CO emission peak, we find that a relatively high star formation efficiency of 8.6 $L_\odot/M_\odot$ is derived for the IGS, which is nearly comparable to that of local starburst galaxies. The IGS triggering mechanism is also briefly discussed.

Subject headings: galaxies: clusters: individual (HCG 92) — galaxies: individual (NGC 7318B, NGC 7319) — galaxies: interactions — galaxies: starburst — infrared: galaxies — intergalactic medium — ISM: molecules

1. INTRODUCTION

Stephan's Quintet (SQ), initially discovered 120 years ago and numbered 92 in the catalog of the Hickson compact groups (HCG 92; Hickson 1982), is one of the most famous and best studied galaxy groups (e.g., Moles, Márquez, & Sulentic 1998). The recent discovery of a prominent intragroup starburst (IGS) in the intragroup medium (IGM) of SQ, far away from the centers of member galaxies, by *Infrared Space Observatory* (*ISO*) mid-IR and ground-based Hα and near-IR observations (Xu, Sulentic, & Tuffs 1999) demonstrates that a starburst can be triggered by a high-speed (~1000 km s^{-1}) collision between an intruder galaxy and a cold IGM.

Despite the richness of the data from multiwavelength observations, there have not been many CO observations obtained to probe the molecular gas content of SQ. At present, it is unknown whether there is any molecular gas readily detectable in the IGS region. Yun et al. (1997) detected CO from the dominant-member Seyfert galaxy NGC 7319 but missed the IGS because of the limited field of view. Even the CO observations of NGC 7319 are controversial; i.e., they are off by a factor of 10 in the estimated molecular gas mass (Leon, Combes, & Menon 1998; Verdes-Montenegro et al. 1998, hereafter V98; Yun et al. 1997). Although SQ is one of the H I–deficient galaxy groups surveyed by a single dish (Williams & Rood 1987), several H I gas concentrations have been detected in the IGM of SQ, especially in the IGS region where ~$10^9\ M_\odot$ H I is detected (Shostak, Sullivan, & Allen 1984, hereafter S84; Williams, Yun, & Verdes-Montenegro 1999; B. A. Williams, M. Yun, & L. Verdes-Montenegro 2000, in preparation, hereafter W00). Should the molecular gas mass of the IGS be close to the H I mass, the detection of CO with current instrumentation would be straightforward, even at the distance of 89 Mpc (H_0 = 75 km s^{-1} Mpc^{-1}, 1″ ~ 0.4 kpc).

Since stars are born from the cold giant molecular clouds (GMCs), CO observations can provide strong constraints to the physical mechanism of the IGS, which is still poorly understood (Xu et al. 1999). It is also of great interest to see whether the molecular IGM can survive in the rather hostile environment in SQ, where large-scale shocks are happening (Pietsch et al. 1997). Previously, the only detections of the IGM molecular gas were in the M81 group (Brouillet, Henkel, & Baudry 1992; Walter & Heithausen 1999), where little star formation is detected (Henkel et al. 1993). Motivated by these considerations, we carried out the CO observations presented in this Letter.

2. OBSERVATIONS

The CO (1–0) observations of SQ have been carried out with the Berkeley-Illinois-Maryland Association (BIMA) 10-element millimeter array at Hat Creek, Northern California. Two compact C-array tracks (with a synthesized beam of ~6″) under good weather conditions (a typical system temperature $\lesssim$300 K and stable phase) were conducted in 1998 October. Judging from Hα and mid-IR observations (Xu et al. 1999), the source size of the IGS may be only a few arcseconds, although weak emission extends to ~20″. Ideally, long-baseline B-array imaging at 2″ is desired in order to study gas properties on a kiloparsec scale. Three B-array tracks were therefore observed in 1999 February/March. However, only one of them was under good weather conditions, whereas the other two were marginal. Thus, more B-array observations have been obtained in 2000 March.

We intended to detect CO emission in the IGS region as well as to confirm the unusual CO features in NGC 7319 detected by Yun et al. (1997). We have thus pointed the BIMA's primary beam (FWHM ~ 110″) to cover NGC 7319, the IGS, and part of the intruder galaxy NGC 7318B. We have tuned the SIS receivers to 112.9356 GHz, corresponding to 6200 km s^{-1}, and configured the correlator to cover a velocity range of 1600 km s^{-1} at a spectral resolution of ~8 km s^{-1} (3.1 MHz). This is because there are at least two H I kinematic systems in the IGS region (S84; W00) and because NGC 7318B is at a velocity 1000 km s^{-1} lower. We have smoothed the data cube to 40 km s^{-1} (~15 MHz) so that the sensitivity achieved allows us to identify any features similar to the complex associations of GMCs observed in the ISM of nearby galaxies.

[1] Infrared Processing and Analysis Center, Jet Propulsion Laboratory, Caltech, MS 100-22, 770 South Wilson Avenue, Pasadena, CA 91125.

[2] Department of Astronomy, University of Toronto, 60 St. George Street, Toronto, ONT M5S 3H8, Canada.

[3] Laboratory for Astronomical Imaging, Department of Astronomy, University of Illinois at Champaign-Urbana, 1002 West Green Street, Urbana, IL 61801.

The source 2203+317 was observed as a phase calibrator, and Uranus/Mars were observed for absolute flux calibrations. We have also applied a Gaussian taper to down-weight long-baseline visibilities in order to compromise the atmospheric decorrelation. The cleaned maps from all the observations combined have a final synthesized beam of 8″.8 × 8″.3.

3. RESULTS

In Figure 1, we compare the integrated CO intensity contours with the *ISO* mid-IR, *R*-band CCD and the continuum-subtracted high-velocity (6600 km s^{-1}) Hα images of SQ. Remarkably, we have detected the CO emission from the IGS with the strongest ∼4 σ detection right at the mid-IR peak (Fig. 1*a*). Also shown are the extracted CO spectra from the data cube for all likely detected features (Fig. 1*b*). On the other hand, the strongest Hα and optical features correspond to a weaker marginal CO feature (nearly 3 σ) rather than the CO peak (Figs. 1*c* and 1*d*). The offset between the CO peak and the Hα and optical peaks could be due to the dust extinction usually associated with CO emission (e.g., in the overlap region of Arp 244; Gao et al. 2000). Examination of the CO spectra and velocity channel maps indicates that the weak CO emission might have been associated with three or four velocity components: high-velocity CO between 6500 and 6750 km s^{-1}, medium-velocity CO around 6200 km s^{-1} and at 6020 km s^{-1}, and possibly the weakest low-velocity CO at 5750 km s^{-1}. All these components (except the one around 6200 km s^{-1}) are at exactly the same velocity ranges of the H I complexes revealed from the VLA observations, although the 5700 km s^{-1} H I component seems to be south of the IGS region and is more related to the intruder galaxy NGC 7318B (S84; W00). There might be Hα emission in the IGS at 5700 km s^{-1}, although this can also be due to the contribution of Hα emission from the 6000 km s^{-1} component (Xu et al. 1999). The 6200 km s^{-1} CO emission appears to be a new component. Yet, its reality needs to be checked by further observations since some negatives also appeared at this velocity in NGC 7319. Of course, high-sensitivity data are obviously required to study better the molecular gas distribution and kinematics in this very interesting IGS region.

We confirm the result of Yun et al. (1997) that the CO distribution in the Seyfert galaxy NGC 7319 is unusually concentrated in two CO complexes. The dominant CO in NGC 7319 resides in the dusty regions in northern tidal features (Fig. 1*c*), which show distinct arclike Hα emission (Fig. 1*d*). The nuclear CO in NGC 7319 is elongated almost perpendicular to the inclined stellar disk, and similar morphology in Hα may have also been observed. We find that the nuclear CO peaks (∼6 σ) almost at the same position (<1″) as the newly obtained VLA 20 cm radio continuum peak (J. J. Condon & C. Xu 2000, in preparation), which could be the Seyfert nucleus. But Yun et al. (1997) claimed that this nuclear CO feature was 2 kpc (∼5″) from the nucleus. Obviously, the stellar disk of NGC 7319 is deficient of both molecular gas and ongoing star formation, except for the inner several kiloparsecs of the nuclear region. Furthermore, the CO emission is almost exclusively at the highest velocity of the entire system, between 6400 and 6800 km s^{-1} in the nuclear region, and narrowly peaks between 6750 and 6870 km s^{-1} in the northern dominant CO complex (Fig. 1*b*).

Two other CO features also appear to be at the ∼4 σ level in the integrated CO intensity map. One is near the center of BIMA's primary beam (shown as the filled circles in Fig. 1) and is probably not real judging from the channel maps and the CO spectrum (labeled as "Beam Center") in Figure 1*b*. This is because no signal at the $\gtrsim$3 σ level is apparent in any channel at this location except at 5700 km s^{-1}. The other, just outside BIMA's beam, is mostly at a velocity of 6250 km s^{-1} and is possibly at 5700 km s^{-1}. This is likely to be associated with some CO clouds near the nuclear region of NGC 7318B since both the location and the velocities might have matched. Nevertheless, CO emission is distributed offset from the nucleus, although very close, and most CO, if real, appears to be at a high velocity of 6250 km s^{-1} rather than 5700 km s^{-1}.

The total CO flux detected from the Seyfert galaxy is 38.7 ± 2.0 Jy km s^{-1} (with only $\frac{1}{4}$ of this from the nuclear region); thus, a molecular gas mass of $M(H_2) = 3.6 \times 10^9\ M_\odot$ using the standard CO-to-H_2 conversion: $M(H_2) = 1.177 \times 10^4 S_{CO}\, dV\, d_L^2\ M_\odot$, where $S_{CO}\, dV$ is the CO flux and d_L is the luminosity distance in megaparsecs. We have observed much more extended CO emission in both CO features as compared with what has been detected by Yun et al. (1997). In particular, the dominant CO has a CO extent of more than 10 kpc.

The total CO emission from the IGS region is more uncertain given the weak features detected. Our estimated CO flux for clumps immediately surrounding the 4 σ peak is ∼4.0 Jy km s^{-1}, but the weak CO extension toward the north appears to have several more clumps with similar or more CO flux of ∼5.0 Jy km s^{-1}. If all these are real, the total CO flux can be as large as 9.0 ± 1.6 Jy km s^{-1}. Therefore, the molecular gas mass closely associated with this IGS region is ∼$3.6 \times 10^8\ M_\odot$ but can be as large as $8.0 \times 10^8\ M_\odot$. This is nearly comparable to the $10^9\ M_\odot$ of H I detected in this IGS region (S84; W00).

Previous observations did not detect any CO emission from the prominent interacting pair NGC 7318A/B (Yun et al. 1997; V98). Our ∼4 σ detection gives a total CO flux of ∼3.1 Jy km s^{-1}, or a molecular gas mass of $2.8 \times 10^8\ M_\odot$ for NGC 7318B even though the feature is just beyond BIMA's beam. In comparison, V98 listed an upper limit of $12.6 \times 10^8\ M_\odot$. Overall, the spatial coincidence of weak CO features with the optical, Hα, mid-IR, and H I emission as well as the matched velocities suggest that most of the CO emission could be real.

4. DISCUSSION

4.1. *Intragroup Starburst: Star Formation Efficiency and Triggering Mechanism*

The reliability of our CO detection of the IGS is strongly supported by two pieces of evidence:

1. The close correlation with the H I gas—not only do the *positions* of the CO signals coincide well with the peaks of the H I components (S84; W00), but the velocity components of the CO emission agree well with those of the H I gas as well (Fig. 1*b*).
2. The CO emission peaks right at the place where the mid-IR emission of the IGS peaks (Fig. 1*a*), which is indeed expected given the close relations of both to massive star formation.

The star formation efficiency (SFE), defined as the ratio of the IR luminosity to the molecular gas mass, is a good indicator of the starburst strength. Sanders & Mirabel (1996) listed that the mean value of the SFE is about 4 $L_\odot/M_\odot$ for normal galaxies and 11 $L_\odot/M_\odot$ for nearby starbursts, and only in luminous (and ultraluminous) infrared galaxies (LIGs) is the SFE

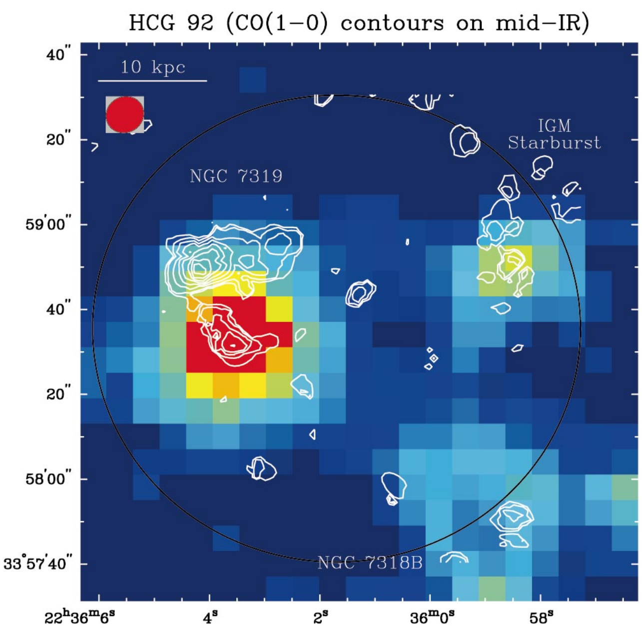

FIG. 1*a*

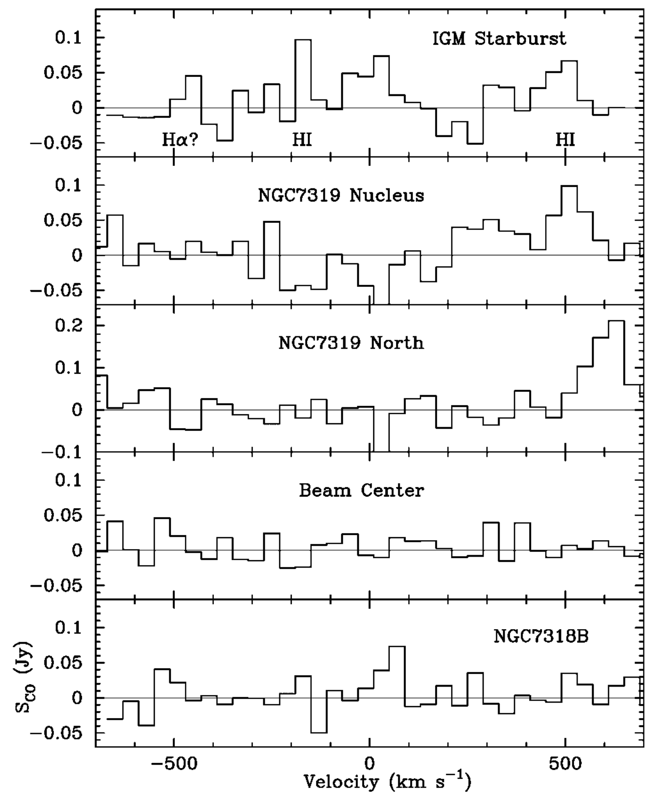

FIG. 1*b*

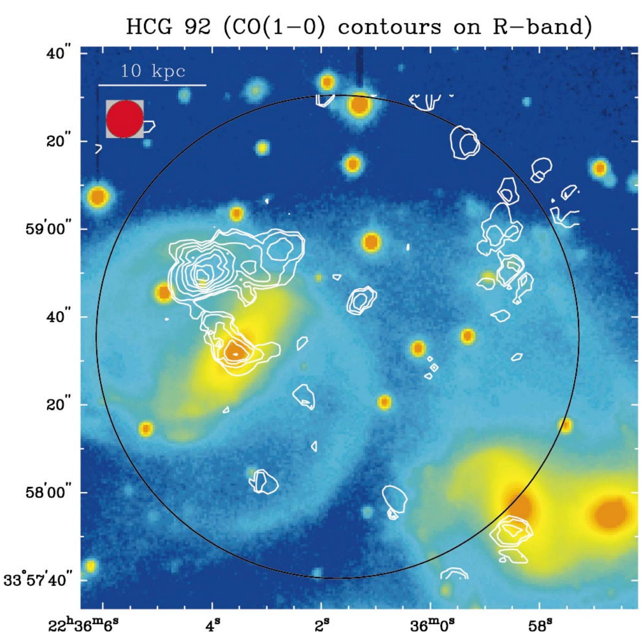

FIG. 1*c*

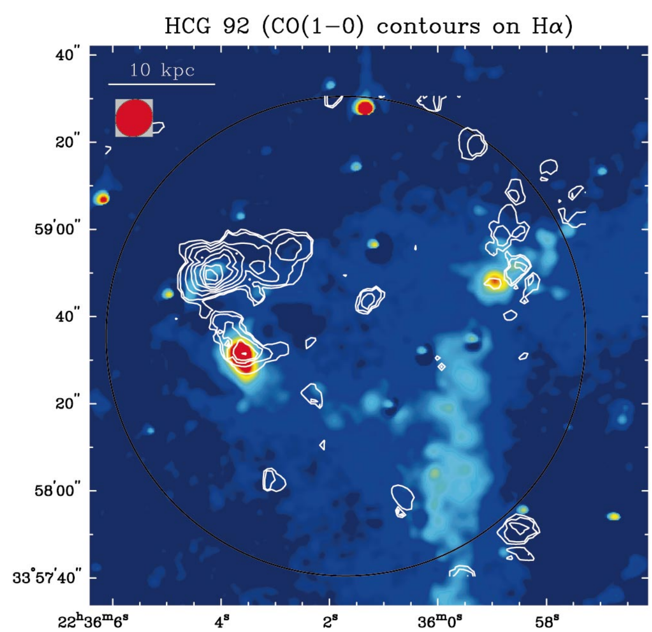

FIG. 1*d*

FIG. 1.—(*a*) *ISO* mid-IR image overlaid with BIMA CO (1–0) integrated intensity contours. The first contour is 2.4 σ, the next one is 3 σ, and then the contours increase by 1 σ. The filled circles indicate the primary beam of 110″ (FWHM). (*b*) Various CO spectra extracted from the data cube for those possibly detected CO features. Zero velocity refers to 6200 km s^{-1}. H I emission peaks and possible Hα components are marked in the panel labeled "IGM Starburst." (*c*) Comparison of CO contours [same as (*a*)] with *R*-band CCD image. (*d*) Same CO contours are compared with the high-velocity 6600 km s^{-1} Hα image.

$\gtrsim$20 $L_{\odot}/M_{\odot}$, which is similar to what has been found in the star-forming cores of GMCs.

For the IGS of SQ, there is no IR luminosity available. Therefore, we carried out the following estimates: (1) We use the mid-IR map (Xu et al. 1999) to scale the IR luminosity of the whole group. The total IR luminosity $L_{\rm IR}$ for the entire group, based on *IRAS* measurements, is $\lesssim 3.61 \times 10^{10}\ L_{\odot}$ since both 12 and 25 μm are upper limits. From Table 1 in Xu et al. (1999), the mid-IR emission of the IGS is about 9% of the total mid-IR emission in the entire field. Assuming that the total IR emission of the IGS is 9% of the total IR emission of SQ, we derive an IR luminosity of $3.2 \times 10^9\ L_{\odot}$ for the IGS. (2) We use the radio continuum emission at 20 cm to derive the far-IR emission based on the well-known correlation between the two since $q = 2.35 = \log\,[F_{\rm FIR}/(3.75 \times 10^{12}\ {\rm Hz})/f_{\nu}(1.49\ {\rm GHz})]$ (e.g., Helou, Soifer, & Rowan-Robinson 1985; Xu et al. 1994). We estimated the radio continuum emission of the IGS region (J. J. Condon & C. Xu 2000, in preparation; see also van der Hulst & Rots 1981) to be $f_{\nu}(1.49\ {\rm GHz}) \sim$ 1.4 mJy. We thus obtained the IR luminosity of $3.1 \times 10^9\ L_{\odot}$ for the IGS, which is same as estimated from the mid-IR map.

Hence, the SFE = 8.6 $L_{\odot}/M_{\odot}$ for the IGS (if the far-IR emission of this region is mostly from the 4 σ peak CO emission) or ~4 $L_{\odot}/M_{\odot}$ (if all weak CO features are real and if the far-IR emission is spread over the entire IGS region). Given the localized nature of starburst and our weak CO detection, we tend to adopt 8.6 $L_{\odot}/M_{\odot}$ as the SFE of the IGS, which is indeed comparable to that of local starburst galaxies.

It is tempting to speculate on the cause of such a high SFE in a rather abnormal environment of the IGM. Generally, a high SFE is associated with high molecular gas concentrations in advanced LIG mergers (e.g., Scoville et al. 1991; Gao & Solomon 1999). For most starburst galaxies (including LIGs), the high gas density is due to the interaction-induced gas infall into the inner few 100 pc of the nucleus during the merging (Sanders & Mirabel 1996). This is certainly not the case for the IGS in SQ, which is far away from any galaxy centers. On the other hand, as noticed by Xu et al. (1999), the IGS is located in a hole of the X-ray emission, and a comparison between our CO map and the new H I map of W00 with the X-ray map of Pietsch et al. (1997) suggests that the highly concentrated cold gas at the place of the IGS could be currently undergoing a squeezing process (or compression) by the surrounding hot gas. This may increase the cold gas density significantly and trigger the high-SFE starburst in the IGM.

The scenario suggested above is different from the one published by Jog & Solomon (1992), in which a starburst occurs when the preexisting GMCs in the colliding disks of LIGs are compressed by the shock-heated hot gas (caused by H I cloud collision) that immediately surrounds them. Because no X-ray emission is detected in the IGS region, such shock-heated hot gas apparently does not exist *within* the region (or is already cooled). Therefore, instead of the individual GMCs being directly squeezed by hot gas, it is more likely that the whole region is being squeezed to a higher density. The starburst is then caused by the high density of the cold gas rather than being a direct consequence of the compression of GMCs as in the Jog & Solomon (1992) scenario.

4.2. *Molecular Gas in SQ: Status Report*

We have detected a larger CO flux in NGC 7319 than the reported single-dish measurements have. While the NRAO 12 m telescope's FWHM beam of 55″ should cover almost all CO features in NGC 7319, the IRAM 30 m telescope's 22″ beam would almost entirely miss the dominant CO in the north (assuming that pointings were good and centered on the Seyfert nucleus). Yet, the 30 m telescope (Leon et al. 1998) obtained a larger CO flux of ~33 Jy km $\rm s^{-1}$, whereas the 12 m telescope (V98) obtained a CO flux of ~18 Jy km $\rm s^{-1}$ for NGC 7319 (compared with ours of 38.7 Jy km $\rm s^{-1}$). Checking the published single-dish CO spectra, both seem to be marginal, and large uncertainties in the CO flux are expected. While the large molecular gas mass of $9.3 \times 10^9\ M_{\odot}$ estimated by Leon et al. (1998) might be an overestimate (they introduced a large scaling factor to account for the large CO source size missed by the 30 m telescope beam), the molecular gas mass of 1.5 × $10^9\ M_{\odot}$ listed in V98 ($8.6 \times 10^8\ M_{\odot}$ in Yun et al. 1997) seems to be too low to compare with the total H I gas mass in SQ. We conclude that for NGC 7319, a more reasonable molecular gas mass is $\gtrsim 3.6 \times 10^9\ M_{\odot}$.

Although the molecular gas mass of the IGS is more uncertain, at a few times $10^8\ M_{\odot}$, it is more massive than the GMC associations in nearby galaxies. This is also much more massive than the molecular complexes discovered in the M81 group (Brouillet et al. 1992; Walter & Heithausen 1999), which has a mass of 10^6–$10^7\ M_{\odot}$. Most of the cold gas (atomic and molecular) concentrated in the IGS region seems to be in the 6600 km $\rm s^{-1}$ component, associated with the preshocked IGM (Allen & Sullivan 1980; S84). This gas was perhaps stripped from NGC 7319 more than 10^8 yr ago (S84; Moles, Sulentic, & Márquez 1997). Because it is usually difficult to strip the molecular gas (which is deeper inside the inner disk than the H I gas is), it is more likely that the molecular gas we detected in the IGS region is condensed locally from the H I gas since the CO peaks right at the H I peak, presumably in connection with the squeezing process suggested above. However, we cannot rule out the possibility that the molecular gas in the IGS region is stripped from NGC 7319, given the large distance of the largest CO complex away from the galaxy center (Fig. 1*a*). In that case, the atomic–molecular gas relation might be completely opposite; i.e., some H I gas in the IGS might be the result of the photodissociation (due to the IGS) of the stripped molecular gas.

Since there are no consistent single-dish observations, we do not know how much of the extended CO emission could still be missed as a result of the zero-spacing problems inherent to an interferometer. Therefore, the sum of the molecular gas mass from all likely detected CO features should be a lower limit to the true total molecular gas content of the entire group. We thus obtain a total molecular gas mass of $\gtrsim 4.7 \times 10^9\ M_{\odot}$ for SQ (mostly in NGC 7319), which is about half of the total atomic gas mass in SQ (Williams & Rood 1987) exclusively distributed *outside* member galaxies in the IGM (S84; W00). Our CO detection in the IGS region of SQ appears to indicate that the molecular gas could also be an important component in the *cold* gas of the IGM ($\gtrsim$30% of the H I gas mass), which can directly provide the fuel for the IGM starburst.

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