CO in Stephan’s Quintet: First Evidence of Molecular Gas in the Intragroup Starburst

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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 covers fully both the IGS region and the dominant group member galaxy Seyfert NGC 7319, as well as partially 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 wavebands (e.g., HI, mid-IR, H\textalpha). Assuming the standard conversion factor, $3.6 - 8.0 \times 10^8$ M\textsubscript{\odot} molecular gas is found to be associated with the IGS. Confining to the region of the CO emission peak, a relatively high star-formation efficiency of $8.6 \text{L}_\odot/\text{M}_\odot$ is derived for the IGS, which is nearly comparable to that of local starburst galaxies (e.g., M82).

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

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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). Recent discovery of a prominent intragroup starburst (IGS) in the intragroup medium (IGM) of SQ, far away from 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 ($\sim 1000$ km s$^{-1}$) collision between an intruder galaxy and cold IGM.

Despite the richness of the data from multi-wavelength observations, little CO observations have been 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 NGC 7319, but missed the IGS due to the limited field-of-view. Even the CO observations of NGC 7319 are controversial, off by a factor of 10 in the estimated molecular gas mass (Leon, Combes, & Menon 1998; Verdes-Montenegro et al. 1998, V98; Yun et al. 1997). Although SQ is one of the HI deficient galaxy groups surveyed by single dish (Williams & Rood 1987), several HI gas concentrations have been detected in IGM of SQ, especially in the IGS region where $\sim 10^9 M_\odot$ HI is detected (Shostak, Sullivan, & Allen 1984, S84; Williams, Yun, & Verdes-Montenegro 1999, 2000 in preparation, W00). Should the molecular gas mass of the IGS be close to the HI 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″ $\sim$ 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 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 are in the group of M81 (Brouillet et al. 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 (synthesized beam $\sim 6''$) under good weather condition (a typical system temperature $\lesssim 300$ K and stable phase) were conducted in Oct. 1998. Judging from Hα and mid-IR observations (Xu et al. 1999), the source size of IGS may be only a few arcseconds although weak emission extends to $\sim 20''$. Ideally, long baseline B array imaging at 2″ is desired in order to study gas properties on a kpc scale. Three B array tracks were therefore observed in Feb./March 1999. However, only one of them was under good weather condition whereas the other two were marginal. Thus, more B array observations have been obtained in March 2000.

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 $\sim 110''$) to cover NGC 7319, 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 $\sim 8$ km s$^{-1}$ (3.1 MHz). This is because there are at least two HI kinematic systems in IGS region (S84; W00) and NGC 7318B is at a velocity $1000$ km s$^{-1}$ lower. We have smoothed the datacube to 40 km s$^{-1}$ ($\sim 15$ MHz) so that the sensitivity achieved allows us to identify any features similar to GMCs complex associations observed in ISM of nearby galaxies.

2203+317 was observed as a phase calibrator and Uranus/Mars for absolute flux calibrations. We have also applied a Gaussian taper to down weight long baseline visibilities to compromise the atmospheric decorrelation. The cleaned maps from all observations combined have a final synthesized beam of $8.8'' \times 8.3''$.

3. Results

In Fig. 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 $\sim 4\sigma$ de-
tection right at the mid-IR peak (Fig. 1a). Also shown are the extracted CO spectra from the datacube for all likely detected features (Fig. 1b). On the other hand, the strongest Hα and optical features correspond to a weaker marginal CO feature (nearly 3σ), rather than the CO peak (Fig. 1c and Fig. 1d). 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 3 or 4 velocity components: high velocity 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 6200 km s$^{-1}$) are at exactly the same velocity ranges of the HI complexes revealed from the VLA observations although the 5700 km s$^{-1}$ component seems to be in south of IGS region (S84; W00). There might be Hα emission in 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 the reality needs additional observations to check as some negatives also appeared at this velocity in NGC 7319. Of course, high sensitivity data are obviously required to better study 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. 1c) which show distinct arclike Hα emission (Fig. 1d). 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 (≈6σ) almost at the same position (< 1″) as the newly obtained VLA 20cm radio continuum peak (Condon et al. 2000, in preparation), which could be the Seyfert nucleus. But Yun et al. (1997) claimed this nuclear CO feature to be 2 kpc ($≈5′′$) from the nucleus. Obviously, the stellar disk of NGC 7319 is deficient of both molecular gas and on-going star formation except for the inner several kpc 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. 1b).

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

The total CO flux detected from the Seyfert is 38.7 ± 2.0 Jy km s$^{-1}$ (with only 1/4 of this from the nuclear region), thus a molecular gas mass of $M(H_2) = 3.6 × 10^8 M_⊙$ using the standard CO-to-$H_2$ conversion: $M(H_2) = 1.77 × 10^4 S_{CO} dV d_l^2 M_⊙$, where $S_{CO} dV$ is the CO flux and $d_l$ is the distance in Mpc. We have observed much more extended CO emission in both CO features as compared to what have 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 4σ peak is $≈4.0$ Jy km s$^{-1}$, but the weak CO extension towards 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 $≈3.6 × 10^8 M_⊙$, but can be as large as $8.0 × 10^8 M_⊙$. This is nearly comparable to the $10^9 M_⊙$ of HI 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 $≈4σ$ detection gives a total CO flux $≈3.1$ Jy km s$^{-1}$, or a molecular gas mass of $2.8 × 10^8 M_⊙$ for NGC 7318B even though the feature is just beyond the BIMA’s beam. In comparison, V98 listed an upper limit of $12.6 × 10^8 M_⊙$. Overall, the spatial coincidence of weak CO features
with the optical, Hα, mid-IR and HI emission as well as the matched velocities suggests that most of 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 HI gas. Not only the positions of the CO signals coincide well with the peaks of the HI components (S84; W00), but also the velocity components of the CO emission agrees well with those of the HI gas (Fig. 1b).

(2) The CO emission peaks right at the place where the mid-IR emission of the IGS peaks (Fig. 1a), which is indeed expected given the close relations of both to massive star formation.

The star formation efficiency (SFE), defined as the IR luminosity to the molecular gas mass ratio, is a good indicator of the starburst strength. The mean values of SFE for normal galaxies is about $4\ L_\odot/M_\odot$, $11\ L_\odot/M_\odot$ for nearby starbursts and only in luminous (and ultraluminous) infrared galaxies (LIGs), $SFE \geq 20L_\odot/M_\odot$ (Sanders & Mirabel 1996), similar to what has been found in the star forming cores of GMCs.

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

Hence, the $SFE = 8.6L_\odot/M_\odot$ for IGS (if the far-IR emission of this region is mostly from the $4\sigma$ peak CO emission) or $\sim 4L_\odot/M_\odot$ (if all weak CO features are real and 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 $8.6L_\odot/M_\odot$ 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, 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 interaction induced gas infall into the inner few 100 pc of the nucleus during the merging (Sanders and 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 comparison between our CO map and the new HI 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 through a squeezing (compression) by the surrounding hot gas. This may increase the cold gas density significantly and trigger the high SFE starburst in 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 shock-heated hot gas (caused by HI clouds 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 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 larger CO flux in NGC 7319 than the reported single-dish measurements. While
the NRAO 12m’s FWHM beam of 55″ should cover almost all CO features in NGC 7319, the IRAM 30m’s 22″ beam would miss almost entirely the dominant CO in the north (assuming pointings were good and centered on the Seyfert nucleus). Yet, the 30m (Leon et al. 1998) obtained larger CO flux of \( \sim 33 \) Jy km s\(^{-1}\) whereas the 12m (V98) gave a CO flux of \( \sim 18 \) Jy km s\(^{-1}\) for NGC 7319 (compared to ours of 38.7 Jy km 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 \( 9.3 \times 10^8 \) \( M_\odot \) 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 30m beam), the molecular gas mass of \( 1.5 \times 10^8 \) \( M_\odot \) 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 HI gas mass in SQ. We seem to conclude that a more reasonable molecular gas mass of NGC 7319 is \( \sim 3.6 \times 10^8 \) \( M_\odot \).

Although the molecular gas mass of IGS is more uncertain, a few times of \( 10^8 \) \( M_\odot \) 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 s\(^{-1}\) component, associated with the preshocked IGM (Allen and Sullivan 1980; S84). This gas is perhaps stripped from NGC 7319 a few \( 10^8 \) years ago (S84; Moles et al. 1997). Because it is usually difficult to strip the molecular gas (deeper inside the inner disk than the HI gas), it is more likely that the molecular gas we detected in the IGS region is condensed locally from the HI gas as the CO peaks right at the HI peak, presumably in connection with the squeezing process suggested above. We cannot rule out the possibility that the molecular gas in IGS region is stripped from NGC 7319, however, given the large distance of the largest CO complex away from the galaxy center (Fig. 1a). In that case, the atomic–molecular gas relation might be completely opposite, namely that some HI gas in IGS might be a result of the photo-dissociation (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 due to 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 \( > 4.7 \times 10^8 \) \( M_\odot \) 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 IGM (S84; W00). Our CO detection in IGS region of SQ appears to indicate that the molecular gas could also be an important component in the cold gas of the IGM, \( > 30\% \) of the HI gas mass, which can directly provide the fuel for the IGM starburst.

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REFERENCES

Williams, B. A., Yun, M., & Verdes-Montenegro, L. 1999, BAAS, 194, #19.05
Fig. 1.— (a) (top left) ISO mid-IR image overlaid with BIMA CO(1-0) integrated intensity contours. Contours start at 2.4, 3σ and increase by 1σ = 1.1 Jy/Beam km s$^{-1}$. The dark circles indicate the primary beam of 110′′ (FWHM). (b) (top right) Various CO spectra extracted from the datacube for those possibly detected CO features. Zero velocity refers to 6200 km s$^{-1}$. HI emission peaks and possible H$\alpha$ components are marked in the panel for ‘IGM starburst’. (c) (bottom left) Comparison of CO contours (same as Fig. 1a) with R-band CCD image. (d) (bottom right) Same CO contours are compared with the high velocity 6600 km s$^{-1}$ H$\alpha$ image.
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