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Molecular Gas in the Intergalactic Medium of Stephan's Quintet

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Abstract. Stephan's Quintet (SQ) is a Hickson Compact Group well known for its complex dynamical and star formation history and its rich intergalactic medium (IGM). In order to study the extent, origin and fate of the intergalactic molecular gas and its relation to the formation of stars outside galaxies and Tidal Dwarf Galaxies (TDGs), we mapped with the IRAM 30m antenna carbon monoxide (CO) towards several regions of the IGM in SQ. In two star forming regions (SQ A and B), situated in very different environments, we detected unusually large amounts of molecular gas (3.1×10^9 $M_\odot$ and 7×10^8 $M_\odot$, respectively), covering an extended area (between 15 and 25 kpc). In both regions the CO clouds have different properties and may be of a distinct nature. The integrated CO line of SQ A is in particular much wider than in SQ B. Its CO spectrum shows emission at two velocities (6000 and 6700 km s^{-1}), coincident with two HI lines, with the stronger emission at 6000 km s^{-1} being very smoothly distributed without a distinct peak in the starburst region. In SQ B the CO emission coincides with that of tracers of star formation (Hα, near-infrared 15 μm and radio continuum). The CO peak lies close to the HI peak towards a steep HI gradient. This is indicating that the molecular gas is forming in-situ, with subsequent star formation taking place. The star forming region at SQ B is the object in SQ that most resembles a TDG.

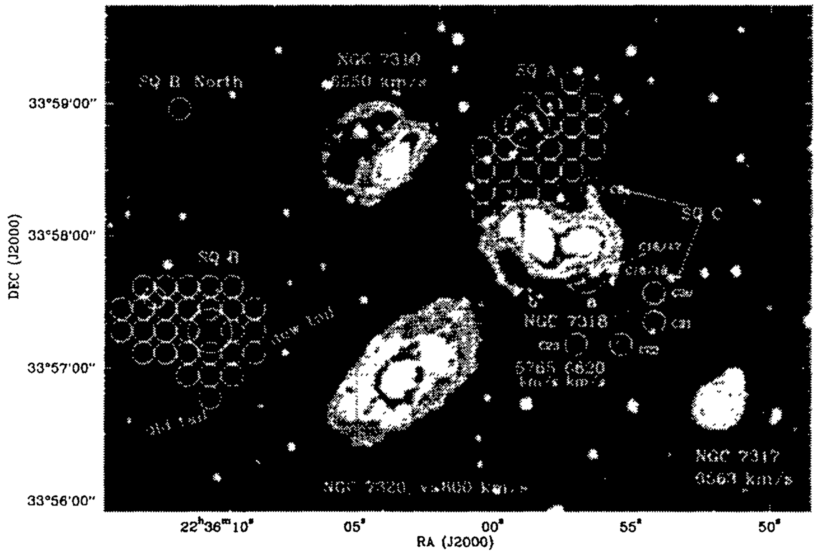

Figure 1. A V-band image of Stephan's Quintet obtained from the CFHT archive. NGC 7320 is a foreground galaxy. The fourth member of the group, NGC 7320c, lies about 4′ east of NGC 7319. The positions observed in CO are indicated by circles. The large circle shows the central (i.e. offset 0,0) position in each region and gives the size of the CO(1–0) beam.

1. Galaxy interaction and intergalactic star formation in SQ

Stephan's Quintet (Hickson Compact Group 92; hereafter SQ, see Figure 1) is one of the best studied examples of a Hickson Compact Group. It contains four interacting galaxies, NGC 7319, NGC 7318a, NGC 7318b, and NGC 7317. One of its most striking properties is that the major part of the atomic gas is in the intragroup medium (Williams et al. 2002), most likely the result of interactions in the past and present.

A plausible scenario for the dynamical history of SQ is presented by Moles, Sulentic, & Márquez (1997). They suggest that a few times 10^8 yr ago the group experienced a collision with NGC 7320c, a galaxy $\sim$4′ to the east of NGC 7319 but with a very similar recession velocity (6583 km s^{-1}, Sulentic et al. 2001) to the other galaxies in SQ. This collision removed most of the gas of NGC 7319 towards the west and east, and produced the eastern tidal tail which connects to NGC 7319. Presently, the group is experiencing another collision, this time with the "intruder" galaxy NGC 7318b, with a recession velocity of 5765 km s^{-1}, which is affecting strongly the intergalactic medium (IGM) which was removed during the first collision. Sulentic et al. (2001), in a multi-wavelength study of the group, confirm this scenario and suggest that the group has been visited twice by NGC 7320c. The first collision created the very faint tidal arm east of the interloper NGC 7320, whereas the second interaction produced the tidal arm which stretches from NGC 7319 eastwards.

This violent dynamical history has induced star formation at various places outside the individual galaxies. ISOCAM mid-infrared and Hα observations have revealed a starburst region (object A in Xu, Sulentic, & Tuffs 1999, hereafter

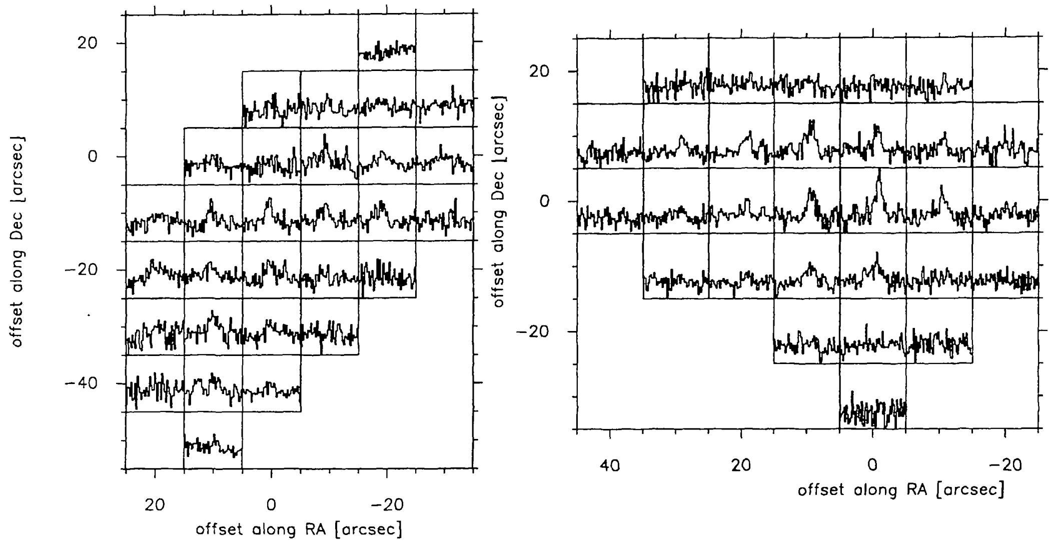

Figure 2. **Left:** CO(1–0) emission in SQ A. The x-scale in the individual spectra is velocity and ranges from 5800 to 6300 $\mathrm{km\,s^{-1}}$. The y-scale is in T_{mb} and ranges from -13 mK to 25 mK. **Right:** CO(1–0) emission in SQ B. The x-scale in the individual spectra is velocity and ranges from 6450 to 6750 $\mathrm{km\,s^{-1}}$. The y-scale is in T_{mb} and ranges from -13 mK to 38 mK.

called SQ A) at the intersection of two faint optical arms stemming north from NGC 7318a/b. Molecular gas has been found at the position of SQ A by Gao & Xu (2000) with BIMA and by Smith & Struck (2001) with the NRAO 12m radio telescope. Both the molecular and the atomic gas in this location present two velocity components, centered at about 6000 and 6700 $\mathrm{km\,s^{-1}}$, which implies that they originate from different galaxies.

A second region where several knots of star formation are found to lie outside the main galaxies is in the tidal arm extending from NGC 7319 to the east. At this position, identified as B by (Xu et al. 1999) and hereafter called SQ B, there is also mid-infrared and Hα emission, although much weaker than in SQ A. Braine et al. (2001), in a study of the CO emission of TDGs, detected $2.9\times10^{8}\,M_{\odot}$ of molecular gas at the position of SQ B. In order to follow up on these detections and to study the extent, origin and fate of the CO in the intergalactic medium (IGM) in SQ, we carried out the single dish survey presented here.

2. Intergalactic molecular gas in SQ

We mapped SQ in July 2001 with the IRAM 30m telescope in CO(1–0) and CO(2–1). Details of the observations and a more complete discussion of the results can be found in Lisenfeld et al. (2002). The positions observed are shown in Figure 1. We mapped (i) the region around the intergalactic starburst

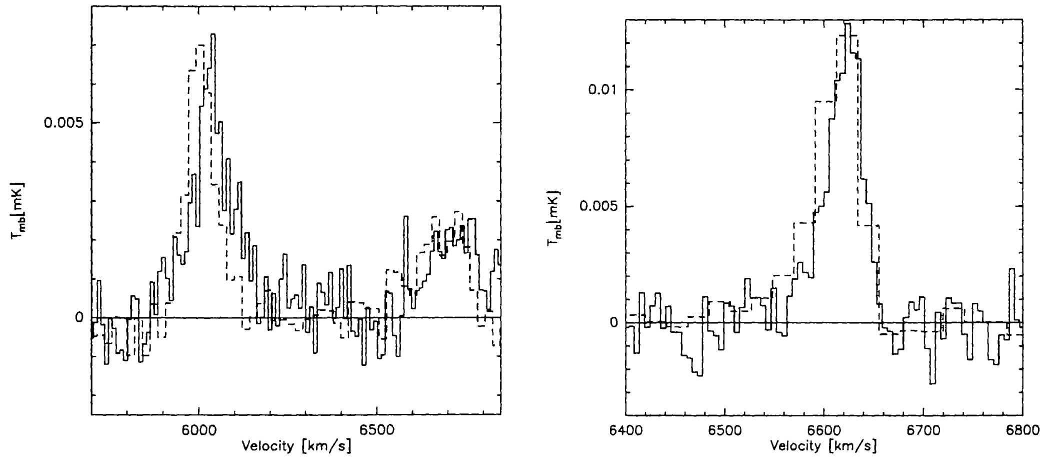

Figure 3. **Left:** CO(1–0) (full line) and HI (dashed line, in arbitrary units, from Williams et al. 2002) spectrum of SQ A, averaged over the total observed area. **Right:** CO(1–0) (full line) and HI (dashed line, in arbitrary units, from Williams et al. 2002) spectrum of SQ B, averaged over the central 15 positions.

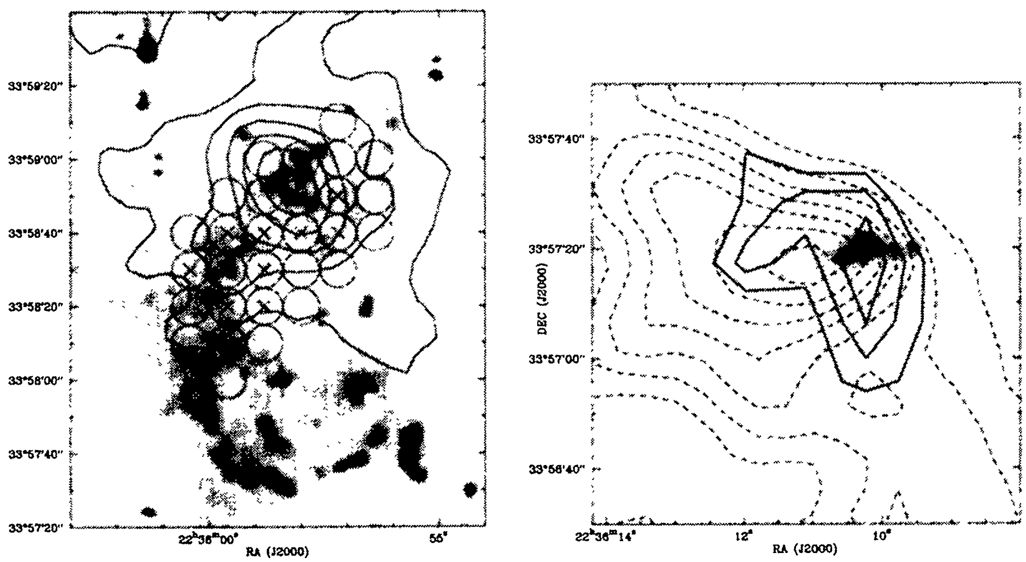

Figure 4. **Left:** A grey scale image of the Hα emission towards SQ A centered at a velocity of 6000 km$\,$s^{-1} (from Xu et al. 1999), overlaid with a velocity integrated HI contour map covering the same velocity (Williams et al. 2002). The circles show the locations of our pointings and the crosses indicate the positions where CO emission was detected above a level of 3σ. **Right:** A grey scale image of the Hα emission towards SQ B centered at a velocity of 6600 km$\,$s^{-1} (from Xu et al. 1999), overlaid with a velocity integrated HI contour map covering the same velocity (Williams et al. 2002, dashed contours), and the velocity integrated CO emission, $I_{\rm CO}$, (full contours, levels at 0.4, 0.65, 0.9 and 1.15 K km s^{-1}).

SQ A, (ii) the area around the star forming region along the eastern tidal tail (SQ B), and (iii) several positions around NGC 7318a/b observed by Mendes de Oliveira et al. (2001) in Hα (labelled as SQ C in Figure 1) and suggested to be candidates for TDGs. At these latter positions no molecular gas was found.

Both in SQ A and SQ B we found extended and abundant molecular gas (see Figure 2), the molecular gas masses being 3.1×10^9 $M_\odot$ and 7×10^8 $M_\odot$, respectively, and with spatial extents between 15 and 25 kpc. The molecular-to-atomic mass ratio is 1.2 (0.5) for SQ A (SQ B), much higher than typical values found in dwarf and tidal dwarf galaxies (Braine et al. 2001). The integrated intensity ratios are similar (CO(2-1)/CO(1-0)=0.69 ± 0.16, respectively 0.56 ± 0.13), consistent with optically thick emission. In both regions, the CO and HI velocities and line shapes agree very well (Figure 3), although in SQ A the CO velocity seems to be shifted slightly to higher velocities with respect to the HI. In SQ A, the CO spectrum shows two velocity components, one at about 6000 km s^{-1}(the velocity of the intruder galaxy NGC 7318b) and the other at 6700 km s^{-1} (the velocity of the rest of the SQ galaxies). Only the component at 6000 km s^{-1} is visible in the individual spectra.

3. SQ A and SQ B – two completely different star-forming regions

SQ A and SQ B are situated in completely different environments: SQ A is part of the region presently affected by the collision with NGC 7318b and hosts shocks as evidenced through X–ray, radio continuum and Hα emission. SQ B is part of the tidal tail situated in a more quiescent area. Therefore it is not surprising that in spite of their similarities (the large amount and extent of the molecular gas, the high molecular-to-atomic gas mass ratio and the similar CO(2–1)/CO(1–0) line ratio) other properties of the molecular gas in SQ A and SQ B are fundamentally different.

The lines in SQ A at 6000 km s^{-1} are very broad (FWHM 60–80 km s^{-1}, see Figure 3), reflecting the wide range of velocities present in the IGM affected by the collision. The CO distribution is rather smooth, spatially offset from the HI emission, with no distinct peak and with only weak emission at the location of the starburst (in Figure 4 the starburst is situated at the peak of the HI emission coincident with Hα knots). Deriving the dynamical mass via a simple estimate from the linewidth and spatial extent, we obtain 1.9×10^{10} $M_\odot$, much larger than the gas and stellar mass in this area ($\sim 3.8 \times 10^9$ $M_\odot$), suggesting that the molecular gas cloud is not gravitationally bound on the size scales at the current resolution. Thus, in SQ A, the extended and homogeneous distribution of the molecular gas makes it unlikely that a gravitational collapse is responsible for its formation. The situation might be different for the emission at 6700 km s^{-1}, for which we cannot constrain the spatial extent because of the weakness of the lines. However, assuming that it closely follows the HI emission at this velocity, which is very concentrated around the starburst, it is likely to be more restricted to the starburst region.

In SQ B, on the other hand, the lines are much narrower (FWHM 30–40 km s^{-1}) and the CO distribution peaks at the star forming region in the tidal arm, close to the peak of the HI emission (Figure 4). The dynamical mass that can be derived from the CO emission (2.9×10^9 $M_\odot$) is comparable to the total gas mass (2.1×10^9 $M_\odot$) and suggests that the molecular gas is gravitationally bound. All this indicates that we are seeing the formation of molecular gas from atomic gas and subsequent star formation. This finding, together with the position of SQ B on the tidal tail and the similarity of its properties to other dwarf galaxies, make it the best candidate for a TDG in SQ.

4. Other cases of intergalactic molecular gas

The first intergalactic molecular clouds were discovered by Brouillet, Henkel, & Baudry (1992) as part of the M 81 group tidal material. Later, a similar object was detected in the same group by Walter & Heithausen (1999). In both cases, no optical counterpart was found. These clouds, with masses of less than 5×10^7 $M_\odot$, might be the first stages of TDGs.

Smith et al. (1999) detected 4×10^8 $M_\odot$ in the tidal tail of Arp 215. In a survey of molecular gas in TDGs Braine et al. (2000) and Braine et al. (2001) detected 8 of 11 objects and derived molecular gas clouds masses between several 10^6 and 3×10^8 $M_\odot$.

These studies show that intergalactic molecular gas in tidal features is a normal phenomenon, in which molecular gas is sometimes detected at distances of up to ~ 100 kpc from the parent galaxies. However, the enormous quantities and large extent of molecular gas found in SQ are unprecedented.

References

Braine, J., Lisenfeld, U., Duc, P.-A., Leon, S., & Brinks, E. 2000, Nature, 403, 867

Braine, J., Duc, P.-A., Lisenfeld, U., Charmandaris, V., Vallejo, O., Leon, S., & Brinks, E. 2001, A&A, 378, 51

Brouillet, N., Henkel, C., & Baudry, A. 1992, A&A, 262, L5

Gao, Y., & Xu, C. 2000, ApJ, 542, L83

Lisenfeld, U., Braine, J., Duc, P.-A., Leon, S., Charmandaris, V., & Brinks, E. 2002, A&A, 394, 823

Mendes de Oliveira, C., Plana, H., Amram, P., Balkowski, C., & Bolte, M. 2001, AJ, 121, 2524

Moles, M., Sulentic. J. W., & Márquez, I. 1997, ApJ, 485, L69

Smith, B. J., Struck, C., Kenney, J. D. P, & Jogee, S. 1999, AJ, 117, 1237

Smith, B. J., & Struck, C. 2001, AJ, 121, 710

Sulentic, J. W., Rosado, M., Dultzin-Hacyan, D., Verdes-Montenegro, L., Trinchieri, G., Xu, C., & Pietsch, W. 2001, AJ, 122, 2993

Walter, F., & Heithausen, A. 1999, ApJ, 519, L69

Williams, B. A., Yun, M. S., Verdes-Montenegro, L., & van Gorkom, J. H. 2002, AJ, 123, 2417

Xu, C., Sulentic, J. W., & Tuffs, R. 1999, ApJ, 512, 178