IR Cooling Lines in Violently Turbulent Environments: From *Spitzer*/*Herschel* to the High-z World

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ABSTRACT

Observations with *Spitzer* of Stephan's Quintet, the Taffy galaxies and several other Hickson Compact Groups showed evidence for enhanced warm molecular rotational lines of hydrogen which suggest strong heating in shocks and turbulence. We present new *Herschel*, CARMA and *Chandra* data of several systems which support the idea that shock/turbulent heating is present in these systems, through a study of the far-IR cooling lines, X-ray luminosity and peculiar CO dynamics. We show that *SPICA/SAFARI* is capable of detecting rotational molecular hydrogen from the brightest known H_2 emitting galaxies (Zw 3146 and the "Spiderweb") to $0.5 < z < 6$ if they exist there, or if less luminous systems are significantly lensed. Turbulent systems may be common at high-z where the most extreme objects are likely to lie in the largest massive dark-matter halos.

1. POWERFUL MOLECULAR HYDROGEN EMITTING GALAXIES (MOHEGS)

During the *Spitzer* mission, it was discovered that there exists a population of galaxy systems with extremely large values of $L(H_2)/L(PAH_{7.7})$ ratio. One of the most striking examples was found in the giant intergalactic filament in Stephan's Quintet (Appleton et al. 2006; Cluver et al. 2010), where the mid-IR molecular hydrogen lines 0–0 S(0),(1)..(5) were found to be the most dominant line coolant. This giant cosmic shock-wave is believed to be caused by the collision of a high-speed intruder galaxy with a suspected tidal filament in this compact group (see Figure 1). Guillard et al. (2009) explained the coexistence of weak X-ray emission and strong molecular hydrogen emission as an effect caused by high speed shocks driven into a multi-phase medium. Another system which showed some similarities with Stephan's Quintet is the Taffy galaxies (UGC12914/5). These galaxies are thought to have recently interpenetrated at high-speed, and have now moved through each other, drawing out a "splash" bridge (Struck 1997; Vollmer et al. 2012) which was first detected in the radio continuum (Condon et al. 1993) as the possible merging and stretching of magnetic fields between them. Like Stephan's Quintet's shock, which is also strongly detected in the radio continuum, Taffy is over-luminous at 20cm compared with its far-IR emission, suggesting that the system is boosted by shocks (Lisenfeld & Völk 2010). Peterson et al. (2012) showed that the bridge between the two galaxies also contains a significant amount of warm molecular hydrogen which cannot be explained by the low-levels of star formation detected in the bridge, but is more likely heated by shocks and turbulence.

Ogle et al. (2010) showed that 20 % of nearby 3CR radio galaxies also showed excessively high warm H_2/PAH ratios, and coined the term MOHEG (Molecular Hydrogen Emission Galaxies) to describe those galaxies with mid-IR spectra dominated by warm emission from molecular hydrogen — most likely from shocks caused by the passage of the radio jets through the host galaxy (see Nesvadba et al. 2010; Nesvadba et al. 2011). Guillard et al. (2012) showed that radio galaxies exhibiting strong HI outflows also were MOHEGs, although in most cases the H_2, although very turbulent, was not outflowing.

Cluver et al. (2013) have studied 78 galaxies in 23 Hickson Compact Groups (HCGs), and discovered that more than 10 % of the galaxies show unusually large H_2/PAH ratios. Moreover, these same galaxies were found to exhibit lower-than-normal specific star formation rates and mid-IR colors, placing many of them in the uv-optical "Green Valley". In this paper, we suggested that one explanation for the "transitional" colors of the galaxies is that shocks are suppressing star formation, causing a drift in color as star formation shuts down. To test this further we proposed to study some of the same objects with *Herschel* and CARMA.

2. FAR-IR COOLING LINES AND CO EMISSION

In order to investigate whether other lines, especially the diffuse ISM cooling lines of [C II] and [O I] were important in the same systems, we recently used *Herschel* to make observations with the PACS IFU spectrometer. Figure 2 and 3 show the results for both the Stephan's Quintet system and the Taffy galaxies. Figure 2 shows initial results from the *Herschel*

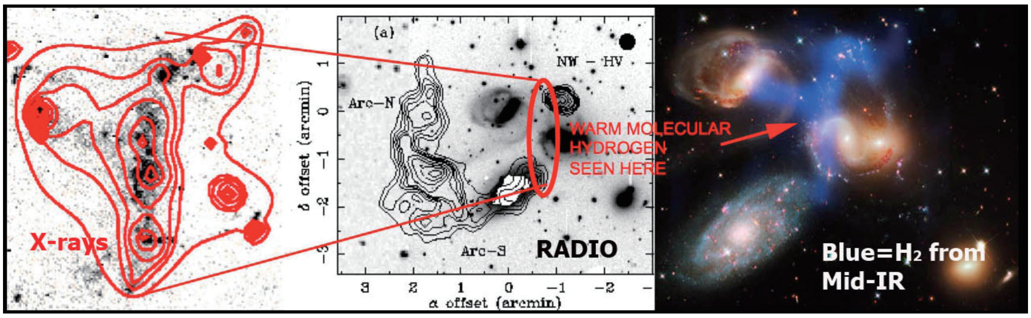

Figure 1. The giant shocked filament in Stephan's Quintet: *Center:* An HI tidal tail (Williams et al. 2002) contains a gap (red oval) where it is believe the high-speed intruder NGC 7318b has struck the tail, causing it to emit both faint soft-Xray emission *left panel:* (Trinchieri et al. 2003), and strong rotational line-emission ($\lambda 17\ \mu$m) from warm molecular hydrogen *right panel:* Blue = H_2 emission superimposed on optical *HST* image: Cluver et al. (2010). The surprising transformation of HI into highly turbulent H_2 in high-speed collisions is one of the discoveries of *Spitzer*.

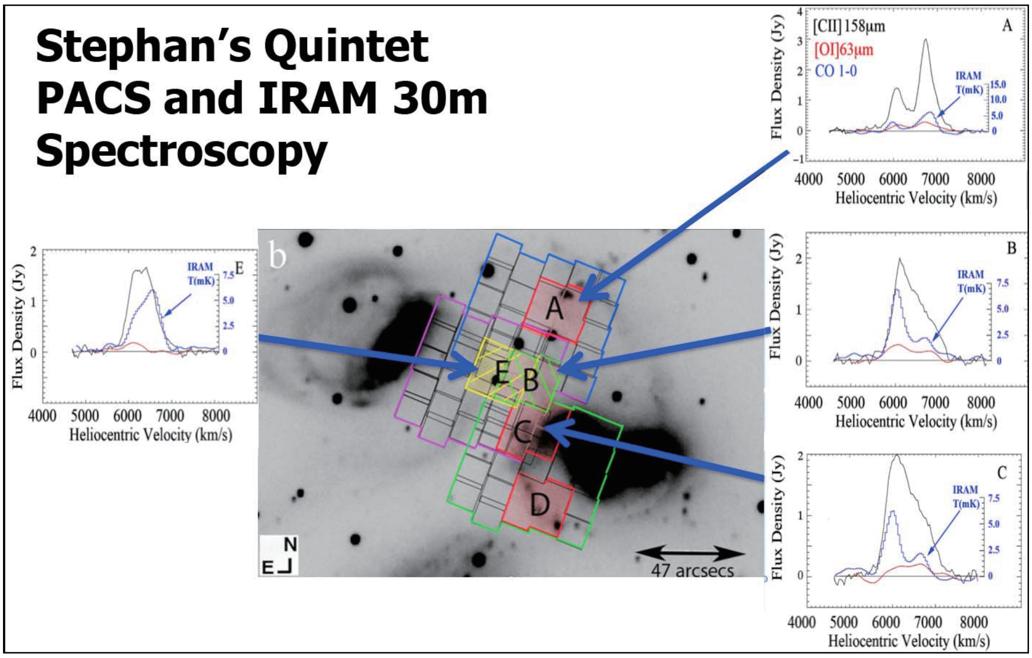

Figure 2. PACS observation footprints and spectra of the [C II]157.7 μm and [O I]63 μm line show the detection of extremely broad emission along and across the giant shock structure in Stephan's Quintet (Appleton et al. 2013). IRAM 30-m spectra taken close to the same positions are also plotted and show similar profiles in CO, suggesting that the molecular and atomic gas phases are well mixed.

imaging of SQ (Appleton et al. 2013). Spectra show the strong detection of very broad (> 1000 km/s) [C II] emission, as well as fainter emission from [O I]63 μm. CO (1–0) observations, obtained with both the IRAM 30-m (Guillard et al. 2012) and more recently with the IRAM PdB interferometer, show clumps of cold molecular gas along the main shock front with velocity profiles similar to that of the [C II], suggesting that the two components are well mixed. Very high [C II]/PAH and [C II]/FIR ratios were detected in several of the regions. The results suggest that [C II] as well as warm H_2 emission are strongly enhanced in the filament by shocks (Appleton et al. 2013).

A 40 ks observation was made of the Taffy galaxies in X-rays with *Chandra* (Wang et al. in preparation), as well as deep photometry and spectroscopy with *Herschel* — see Figure 3. Again strong [C II] emission is detected in the northern bridge in the same region as weak soft X-ray emission is detected. Like Stephan's Quintet, the [C II]/PAH and [C II]/FIR ratios are elevated compared with normal galaxies, and the X-ray emission is faint enough that it cannot be responsible for heating the molecular gas and exciting the [C II] transition. We believe that cosmic-rays, which are obviously present in the bridge (since we detect radio synchrotron), are also insufficient to explain the heating. Turbulent energy dissipation is the most likely cause of the heating of the warm gas seen between the galaxies. Such turbulence is expected to decay on a timescale of 10–20 million years, and can provide plenty of energy to heat the medium — causing a boost to the mid- and far-IR line emission over that expected from UV heating from stars alone.

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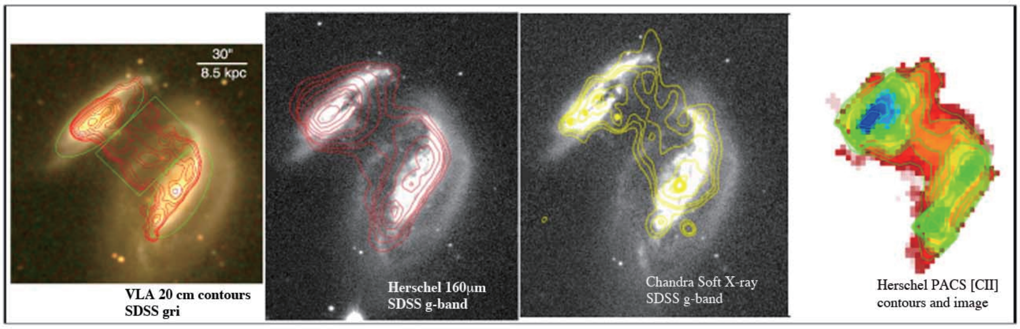

Figure 3. The main faces of the Taffy galaxies (from Wang et al. and Peterson et al. in preparation) from our *Chandra* and *Herschel* programs.

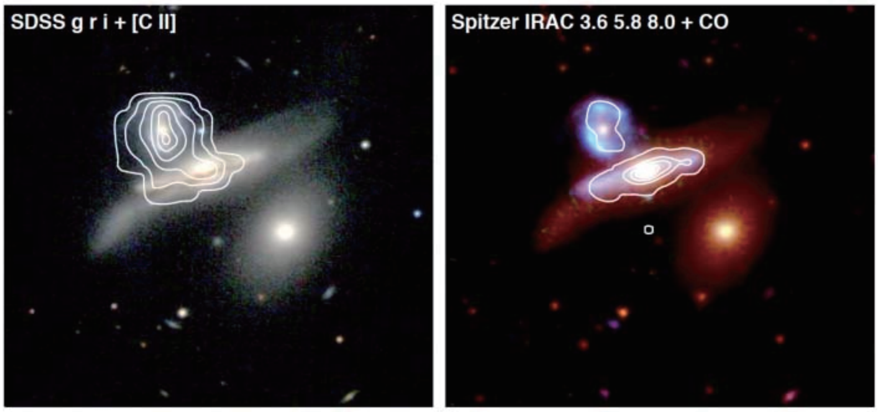

Figure 4. Part of our *Herschel* and CARMA program to map [C II], [O I] and CO in H_2 enhanced Hickson Compact Group galaxies (Alatalo et al. in preparation). *Left:* [C II] contours superimposed on an optical image of the inner HCG57 group and *Right* a Combined Array for Millimeter Astronomy (CARMA) image of the integrated CO (1–0) emission from the galaxies. The edge-on galaxy HCG57A is a MOHEG (Cluver et al. 2013). The northern ring-like galaxy HCG57d was unfortunately not observed by *Spitzer* in molecular hydrogen. Note the large difference in [C II]/CO ratio between the two galaxies detected.

Our team has recently begun to follow-up the Cluver et al. (2013) sample of HCG MOHEGs with *Herschel* to study the far-IR lines and dust continuum properties, but also to investigate the distribution and dynamical state of the colder molecular gas through CARMA CO imaging. The first example of such a study (Alatalo et al. in preparation) is shown in Figure 4. The results show interesting differences in the [C II]/CO ratio in the two galaxies, HCG57d, the smaller northern galaxy has usually large [C II]/CO and [C II]/FIR ratios compared with the southern galaxy. Although such effects could be due to low metallicity, optical spectra do not support this. Although the raised [C II] emission could be due to a large ionized component to the galaxy (this is under examination by IFU optical imaging), the similarities with the Taffy are striking. The MOHEG galaxy (HCG57A — the edge-on galaxy) has less extreme integrated properties, but shows very peculiar CO dynamics, exhibiting a possible nuclear CO outflow, as well as double-line profiles in the north-western disk. Like the Taffy, these galaxies may be examples of a near-head-on collision which has created highly turbulent conditions in the disks of both galaxies.

3. *SPICA* AND THE HIGH-REDSHIFT UNIVERSE

Before *Spitzer* ran out of cryogen, it detected a number of very powerful H_2-emitting galaxies, including several central cluster galaxies (e.g. Zw 3146 at $z = 0.3$; Egami et al. 2006), where the H_2 line luminosity is an order of magnitude brighter than those seen in individual galaxy collisions. Shocks and or cosmic ray heating may be responsible for some of these large luminosities, but by far the most powerful warm H_2 emitting system was detected by Ogle et al. (2012) in the $z = 2.15$ radio galaxy proto-cluster PKS1138-26 (knows as the *Spiderweb*). The luminosity is a single H_2 rotational line (the 0–0 S(3) line at $\lambda_{\rm rest} = 9.66\,\mu$m), was a phenomenal 1.44×10^{44} ergs s^{-1}, with a strong likelihood that this is a low-limit to the total H_2 power, and over 100× brighter than Stephan's Quintet. Although this system is clearly not in the same category as the nearby MOHEGs (the star formation rate in the central galaxy is in the range 500–1200 $M_\odot$ yr^{-1}), nevertheless the extended structure of the *Spiderweb*, and its large associated proto-cluster dark matter halo, suggests the possibility that some fraction of the H_2 luminosity might be mechanical heated via shocks and turbulence.

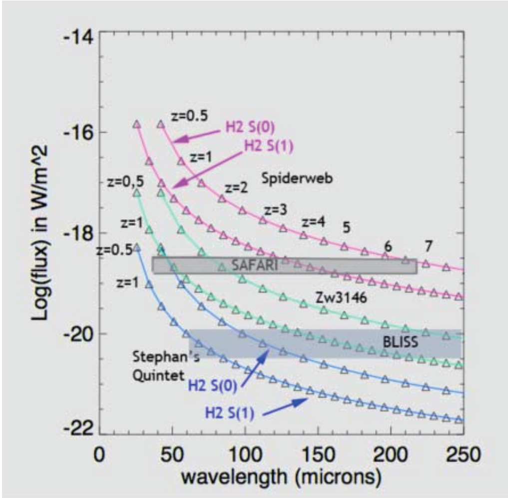

Figure 5. Estimates of the 0–0 S(0) 28 μm and 0–0 S(1) 17 μm ground-state pure-rotational H_2 line fluxes (W m^{-2}) for the Spiderweb (PKS1138-26) and the central cluster galaxy in Zw 3146 shifted in increments of $\Delta z = 0.5$ as a function of observed wavelength. For the Spiderweb it is assumed that these lines are equally as bright as the observed 0–0S(3) line (0.41×10^{-17} W m^{-2} of Ogle et al. 2012), and the S(3) line (2.3×10^{-17} W m^{-2}) for Zw 3146 (Egami et al. 2006) and a standard ΛCDM cosmology assumed. The horizontal lines represent the effective limit of detection with *SPICA*/SAFARI. To detect fainter object we must await future far-IR missions with instruments like BLISS (Bradford et al. 2010) that would be capable of going deeper.

The existence of such extreme H_2 emitters begs the question of whether H_2 could be used to probe turbulence in the early universe (see Appleton et al. 2009). Up to a redshift of ∼15, the rotational H_2 lines are within the far-IR domain, and can barely be reached by ALMA. Figure 5 shows a plot of the sensitivity limits of *SPICA*/SAFARI (Roelfsema et al. 2012) for H_2 line luminosities in the 0–0 S(0) and 0–0 S(1) rotational molecular hydrogen lines assuming similar luminosities for the most extreme known H_2 emitters. If Spiderweb-like sources exist up to $z = 6$, the S(0) and S(1) lines could be detected with SAFARI, and to $z = 1.5$ for sources like Zw 3146. Most sensitive studies will have to exploit high-z lensing amplification, or employ more sensitive low-resolution spectrometers on future telescope, like the BLISS instrument proposed by Bradford et al. (2010). Higher-order rotational transitions could also be probed by *JWST* in the mid-IR, but if most of the power was concentrated in the lowest-order rotational states (cool gas), the far-IR may be the only way to directly detect rotational H_2 emission from turbulent primordial clouds.

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