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A Herschel and CARMA view of CO and [C II] in Hickson Compact groups.

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Abstract. Understanding the evolution of galaxies from the starforming blue cloud to the quiescent red sequence has been revolutionized by observations taken with *Herschel* Space Observatory, and the onset of the era of sensitive millimeter interferometers, allowing astronomers to probe both cold dust as well as the cool interstellar medium in a large set of galaxies with unprecedented sensitivity. Recent *Herschel* observations of of H_2-bright Hickson Compact Groups of galaxies (HCGs) has shown that [C II] may be boosted in diffuse shocked gas. CARMA CO(1–0) observations of these [C II]-bright HCGs has shown that these turbulent systems also can show suppression of SF. Here we present preliminary results from observations of HCGs with *Herschel* and CARMA, and their [C II] and CO(1–0) properties to discuss how shocks influence galaxy transitions and star formation.

Keywords. galaxies: elliptical and lenticular, cD - galaxies: evolution - galaxies: formation

1. Introduction

Compact groups are defined as "small, relatively isolated systems of typically four or five galaxies in close proximity to one another" (Hickson 1997). They tend to have a high fraction of early-type galaxies (E/S0), evidence of tidal interactions, are high density with low velocity dispersion (Hickson 1997) and are generally deficient in H I (Verdes-Montenegro et al. 2001; Borthakur, Yun & Verdes-Montenegro 2010). Compact groups appear to go through an evolution (Fig. 1; Verdes-Montenegro et al. 2001) that can be traced based on its neutral gas depletion (Verdes-Montenegro et al. 2001), with galaxies the most advanced group stages no longer containing their own interstellar medium, and instead being surrounded by a common envelope (Rasmussen et al. 2008).

Johnson et al. (2007) documented a marked "infrared gap" in compact group galaxies, with very few galaxies observed between the star-forming cloud and the quiescent cloud. Cluver et al. (2013) showed that the "gap" galaxies in compact groups tended to have warm hydrogen emission (traced by the *Spitzer* Infrared Spectrograph) that was enhanced beyond the point that simple radiative processes could explained, deemed Molecular Hydrogen Emission Galaxies (MOHEGs; Ogle et al. 2006). Cluver et al. (2013) were able to show that the enhanced H_2 emission was most easily explained via shocks. With the onset of the Wide-field Infrared Survey Explorer (WISE), this infrared transition zone was shown to be more universal, with the bifurcation between early-type and late-type galaxies present in a large sample of galaxies (Alatalo et al. 2014a). Understanding this transition takes both a broad survey approach, as well as carefully selected case studies.

Using the Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al. 2010) on *Herschel* (Pilbratt et al. 2010), we observed ISM cooling lines, primarily [C II] and [O I] of HCGs, and directly compare the ISM cooling to the molecular gas, traced via the Carbon Monoxide (CO) line, observed using the Combined Array for Research in Millimeter Astronomy (CARMA).

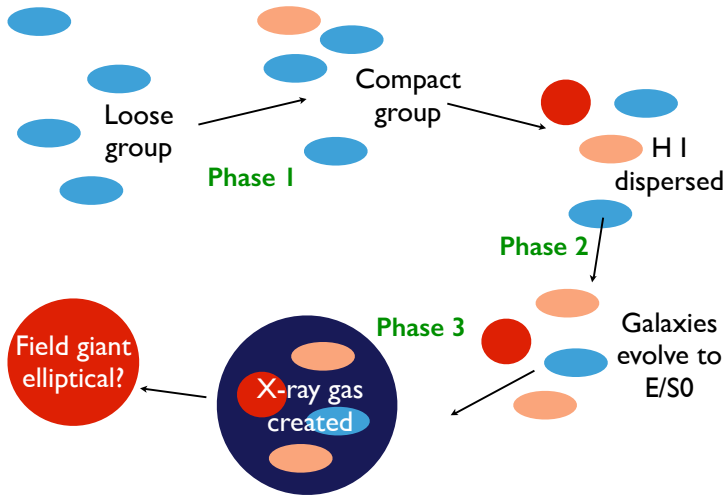

Figure 1. A schematic of the proposed HCG evolutionary picture. The H I observations taken by Verdes-Montenegro et al. (2001) and Borthakur, Yun & Verdes-Montenegro (2010) support the Hickson (1997) picture in which galaxies start in a loose group, move into the compavt group phase (during which the H I in the individual galaxies are dispersed) until the gas is located within a common envelope. During the evolution of the ISM, the galaxies within the group are also transitioning (Johnson et al. 2007; Walker et al. 2010, 2013; Cluver et al. 2013).

2. Observations and Reduction

11 HCGs were observed with CARMA over the course of three semesters between 12 Mar 2013 – 16 Jun 2014, and one, HCG 96 was taken from the archive, totaling 12 HCGs and 14 individual galaxies. Raw data were reduced and calibrated identically to the ATLAS^{3D} galaxies (Alatalo et al. 2013). Figure 2 shows the integrated intensity and mean velocity map of HCG 96, as an example of the data quality that has been attained by the CARMA observations. CO in many of the HCGs have also been observed with single dish telescopes (Martinez-Badenes et al. 2012; Lisenfeld et al. 2014). For the most part, the fluxes from CARMA agree with the single dish fluxes, although in the cases of larger, more extended sources, CARMA recovers more flux than the single dish in cases where only a single pointing was observed.

Herschel PACS [C II] and [O I] observations were taken of 11 HCGs, and the data were reduced using Herschel Interactive Processing Environment (HIPE) software package CIB13-3069, and data were analyzed identically to HCG 57, described in Alatalo et al. (2014b). [C II] was detected in all 11 groups, and [O I] was detected in 9. Of the 11 PACS-imaged HCGs, 9 were detected in CO (Lisenfeld et al. 2014) and 8 were imaged using CARMA.

3. Discussion

In normal galaxies, [C II] can be a reliable tracer of SF (de Looze et al. 2011), but this relation begins to break down as soon as one begins investigating the outliers. Observations have shown that in local galaxies, $L_{[C\,II]}/L_{FIR}$ decreases in intense starburst environments (e.g. local ULIRGs; Malhotra et al. 2001; Luhman et al. 2003) and high-z quasars, but the "deficit" may relate to the intensity of the UV radiation field. Díaz-Santos et al. (2013) observed that $L_{[C\,II]}/L_{FIR}$ decreases as a function of infrared luminosity in LIRGs, and thus in the most prolific star-formers, [C II] underestimates the true star formation rate. Figure 3a shows the inverse of the Díaz-Santos et al. (2013) result when one observes a selection of shocked galaxies (including Stephan's Quintet, Taffy and HCG 57). In most "normal" galaxies, $L_{[C\,II]}/L_{FIR}$ rarely exceeds

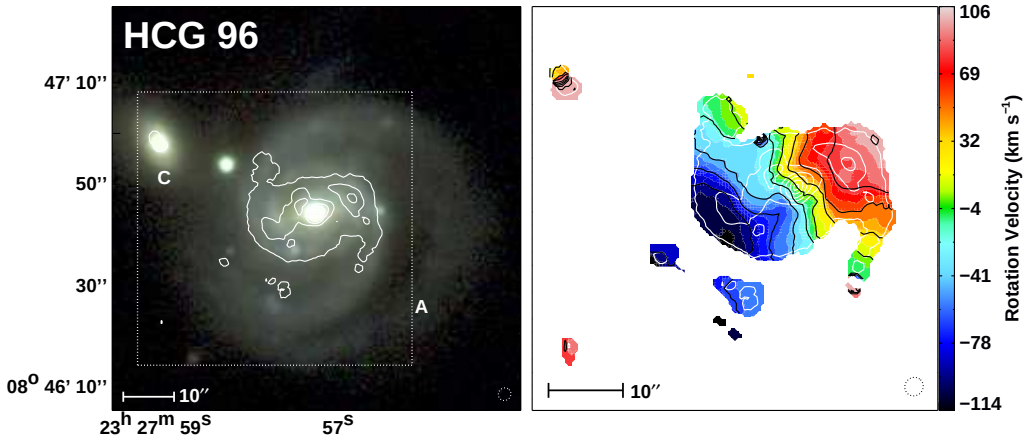

Figure 2. An example of the CO data from CARMA. **(Left):** The Sloan Digital Sky Survey *g*, *r*, *i* image underlies the moment0 map of HCG 96a and 96c (labeled on the diagram), which were both detected in the CARMA pointing. **(Right):** The mean velocity map of HCG 96a and 96c. In HCG 96a, the velocity structure traces the spirals, and in HCG 96c, the molecular gas is centralized, and regularly rotating.

1%. In these shock-dominated objects Peterson et al. 2012; Cluver et al. 2013; Appleton et al. 2013; Alatalo et al. 2014b, there are many more regions that exceed this 1% "ceiling". These examples show that one must exercise caution when using $L_{[C\ II]}$ to determine the SF in an object, but it also shows that [C II] is capable of pinpointing turbulence in systems.

Compact group galaxies whose ISM is turbulent, likely due to direct collisions that cause shocks, are also the galaxies that appear to contain the least efficient molecular gas. This observation is supported by the fact that both Stephan's Quintet and HCG 57 show enhanced [C II]/L_{FIR} and signs of suppressed SF (Guillard et al. 2012; Appleton et al. 2013; Alatalo et al. 2014b). Lisenfeld et al. (2014) studied the CO properties of MOHEGs and non-MOHEGs in HCGS, and, although several objects in their sample showed a suppressed SF, they did not find a statistical difference between the star formation efficiency of MOHEGs compared to non-MOHEG sources. This might mean that excited H2 emission does not influence the star formation of an entire galaxy.

Figure 3b compares the H_2 mass to the SF rate. The colorization is based on the distance off of the Kennicutt-Schmidt relation ($\Sigma_{SFR} = 2.5 \times 10^{-4} \Sigma_{gas}^{1.4}$; Kennicutt 1998). Interestingly, this figure shows that many of the HCG galaxies studied for this survey lay below the K-S relation, with several showing considerable (> 10) suppression. Two MOHEGs (including HCG 57a) represent the most suppressed objects. Given that galaxies in HCGs are much more likely to experience frequent interactions than field galaxies, they are ideal test beds for how turbulence can impact star formation. The fact that these systems are more likely to lie below the K-S relation than above is intriguing. However, a larger number of objects and a more detailed study is neceesary to confirm this trend. The [C II] imaging from Herschel will allow for a much more in-depth look at galaxies, determining areas of high turbulence within galaxies, and investigating whether those regions show signs of suppression. The recent study on HCG 57a, which used this method, seems to confirm the utility of this method.

We are following up on these galaxies to determine where they lie in context, including whether they are found within the optical green valley or the infrared transition zone, to see if the suppression of star formation is a cause, or a symptom of this transition. Further [C II] and CO(1–0) are needed of a larger sample of transitioning galaxies to fully understand this population, and in particular, how turbulence and shocks impact the supply of the cold molecular gas, as well as the how existing molecular gas forms stars.

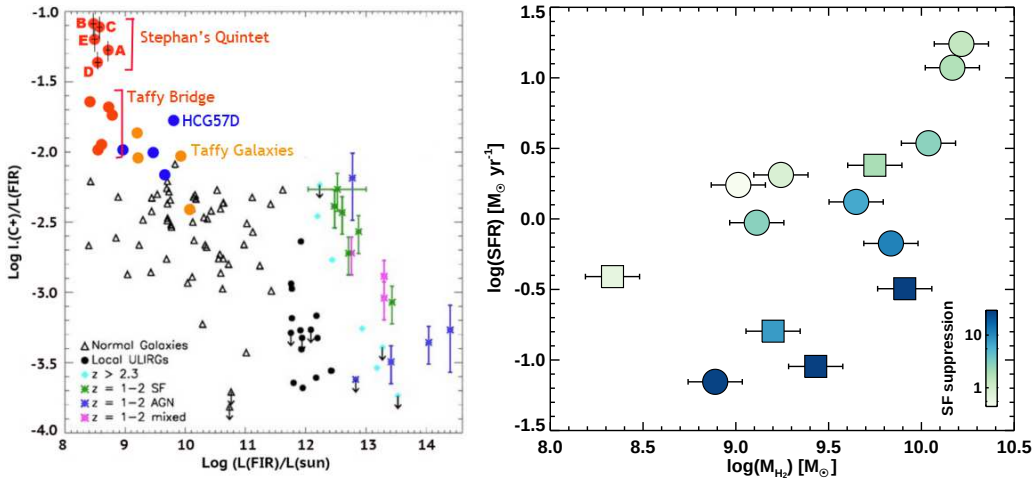

Figure 3. (Left): The L([C II])/L_{FIR} vs L_{FIR} of starforming galaixes and ULIRGs (Malhotra et al. 2001) and high$-z$ sources (Stacey et al. 2010). There is an approximate L([C II])/L_{FIR} upper limit of 1%, until we include sources known to have shocks, including the Taffy Galaxies (Peterson et al. 2012), Stephan's Quintet (Appleton et al. 2013) and HCG 57 (Alatalo et al. 2014b). **(Right):** The total star formation rate calculated from Bitsakis et al. (2014), normalized to a Salpeter initial mass function (Salpeter 1955) compared to the molecular gas mass derived from the CO(1–0) data from CARMA (using the L_{CO}–to–M_{H_2} conversion of $2.\times10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$; Bolatto et al. 2013). The colorization is based on the distance off of the relation derived in Kennicutt (1998).

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