The Impact and Fate of the ISM in Compact Groups of Galaxies

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ABSTRACT

Compact groups of galaxies provide a unique environment to study the evolution of the ISM and mechanisms by which star formation occurs amid continuous gravitational encounters. We present Spitzer, 2MASS, and HI observations of a sample of 12 Hickson Compact Groups (HCGs) and a total of 45 galaxy members. The galaxies in this sample have observed infrared characteristics that are distinctly different from the sample of field galaxies in the Spitzer FLS or SINGS. Most notably, HCG galaxies exhibit a "gap" in infrared color space, separating gas-rich groups from gas-poor groups, that is sparsely populated and which is not seen in either the FLS or SINGS. This gap may suggest a rapid evolution of galaxy properties in response to dynamical effects in HCGs. Moreover, there are striking trends seen between the ratio of HI mass to dynamical mass for an entire group and the infrared colors of the individual member galaxies. These trends suggest that the constituent galaxies in compact groups are related to the type of group in which they reside. The results of this project can provide insight for the earlier universe when environments similar to those found in compact groups of galaxies were common.

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1. Introduction

The remarkable density of matter that defines the compact galaxy group is rather similar to the inner core of a massive galaxy cluster. Yet unlike clusters, their unusually low velocity dispersions betray the unique nature of compact group – most notably their ability to undergo long-duration dynamic interaction between galaxy members (Hickson et al. 1992). Accordingly, the majority of HCG galaxies exhibit morphological peculiarities that arise from tidal disturbance (e.g., Mendes de Oliveira & Hickson 1994). Perhaps the most spectacular example of a multiple interaction is Stephan's Quintet, for which Trinchieri et al. (2003) and Appleton et al (2006) revealed, through x-ray and resolved molecular hydrogen emission, a gigantic and powerful intergalactic shock wave that neatly defines a four-galaxy collision interface. Compact groups are therefore excellent laboratories to study tidal interactions and their subsequent effect on star formation evolution and ISM processing. For example, based on IRAS observations, Hickson et al. (1989) find that infrared emission (tracing star formation) in compact groups is enhanced with respect to isolated galaxies. On the other hand, Allam et al. (1995) and Verdes- Montenegro et al. (1998) find that compact group galaxies exhibit a normal level of infrared emission compared to control samples of isolated galaxies, which suggests that the tidal activity in their sample does not generally enhance star formation. These differences are likely due to the evolutionary state in which the HCG is observed, and thus sample and wavelength selection is critical to working with HCGs. A more comprehensive look at the star formation properties of compact groups is now possible with the *Spitzer* Space Telescope, which may resolve these inconsistencies. In this brief report and in more extensive work of Johnson et al. (2007) and Gallagher et al. (2008) we present Spitzer IRAC/MIPS observations of a sample of 12 Hickson Compact Groups (HCGs) that includes detailed study of 45 galaxy members, spanning a wide range in physical properties. The primary science goal is to establish a physical/causal connection between global and local compact group galaxy properties.

2. Sample Selection & Observations

We obtained *Spitzer* observations using IRAC 3.6, 4.5, 5.8 & 8.0μm and MIPS 24μm imaging for 12 HCGs (Hickson et al. 1992) that are known to have at least 3 accordant members, and which were selected based on distance (<4500 km s^{-1}), angular size (<80$''$) and H I content (from gas-rich to gas-poor; the H I masses are from Verdes-Montenegro et al. 2001). The neutral gas content serves as a proxy to the evolutionary state of the group. The resulting sample is shown in Fig. 1. Standard data reductions were carried out, including careful calibration of the extended source emission; see Johnson et al. (2007) for more details.

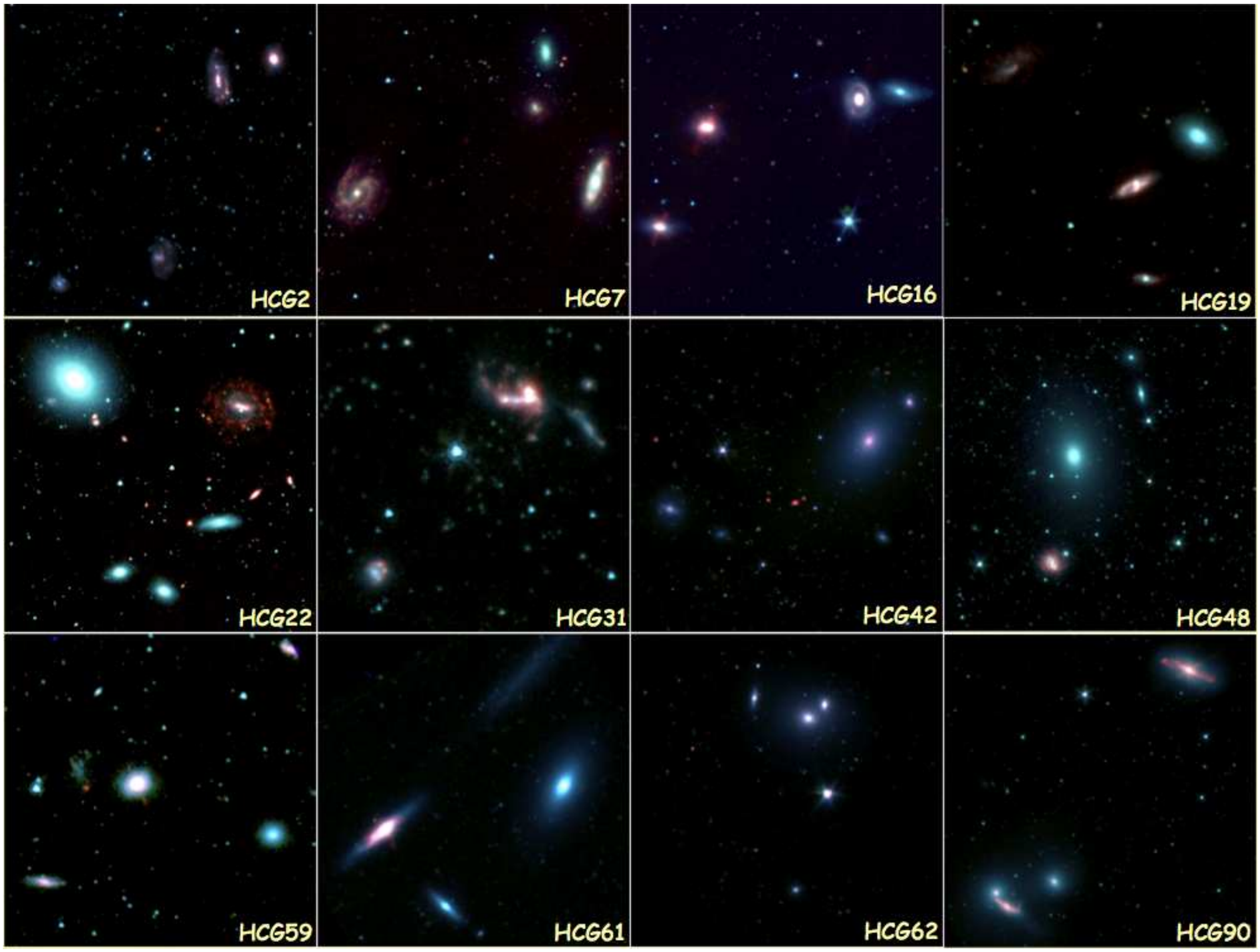

Fig. 1.— IRAC images of the sample compact groups. The bands are color-combind in the usual fashion: IRAC ch1 (3.6μm) = blue, ch2 (4.5μm) = green, ch4 (8.0μm) = red. The colors clearly reveal the wide diversity in star forming properties between HGGs.

3. Evolutionary Stages

Our sample include compact groups in each of the three stages of the evolutionary sequence described by Verdes-Montenegro et al. (2001): preinteraction, shocked intergroup medium, and smooth intergroup medium, respectively. Although these broad categories greatly simplify the actual complexity of HCGs evolution, we have found that comparing the H I gas mass with the dynamical mass provides a useful way to quantify and study these stages of group evolution. The dynamical masses are calculated from velocity dispersions and median galaxy separations in Hickson et al. (1992), Ribeiro et al. (1998), and /or Zimer et al. (2003).

Our proposed modification to the "evolutionary states" for HCGs is to evenly divide the sample according to the gas to dynamical mass ratio, $\log(M_{\mathrm{HI}})/\log(M_{dyn})$, such that:

- **Type I** – relatively H I rich > 0.9
- **Type II** – moderate gas content $> 0.8 - 0.9$
- **Type III** – relatively poor H I < 0.8

These broad divisions were chosen in order to uniformly spread our sample into roughly equal thirds, which is more than adequate to separate the basic star-forming properties of the compact groups; see Figure 2, where the Hubble Type roughly tracks the evolutionary state of the individual members and the 24μm luminosity tracks the star formation activity.

As would be expected, the groups that are relatively gas rich, tend to have the most late-type galaxies, and conversely, the gas-poor groups tend to have the most early type galaxy members. This would be a trivial relationship if the gas were exclusively residing in the member galaxies; however, the gas is typically distributed throughout the group and its intergalactic medium. So the relationship between the group type and individual galaxy properties is more complex than the straightforward view. For example, note the bimodal structure in the Hubble type distribution (Fig 2a, top panel); which suggests that galaxies in compact groups may rapidly transform between late and early types; see below.

4. Spectral Energy Distributions

Example SEDs for HCG galaxy members are shown in Fig. 3. The photometry corresponds to 2MASS JHK isophotal aperture measurements and (matched aperture) extractions from IRAC and MIPS that include extended source corrections[1]; details given in Johnson et al 2007.

The early or pre-interaction evolutionary stage (I) is represented by HCG 16; Fig 3a, characterized by a steepening mid-infrared (MIR) spectrum arising from PAH and warm dust emission. Interestingly, Ribeiro et al. (1998) identified this HCG to be a core + halo system, with the compact group the luminous component of a larger collapsing structure.

The intermediate stage is represented by HCG59; Fig 3b, which has strong stellar emission and weak PAH emission relative to a rising warm dust continuum.

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[1] See http://ssc.spitzer.caltech.edu/irac/calib/extcal/

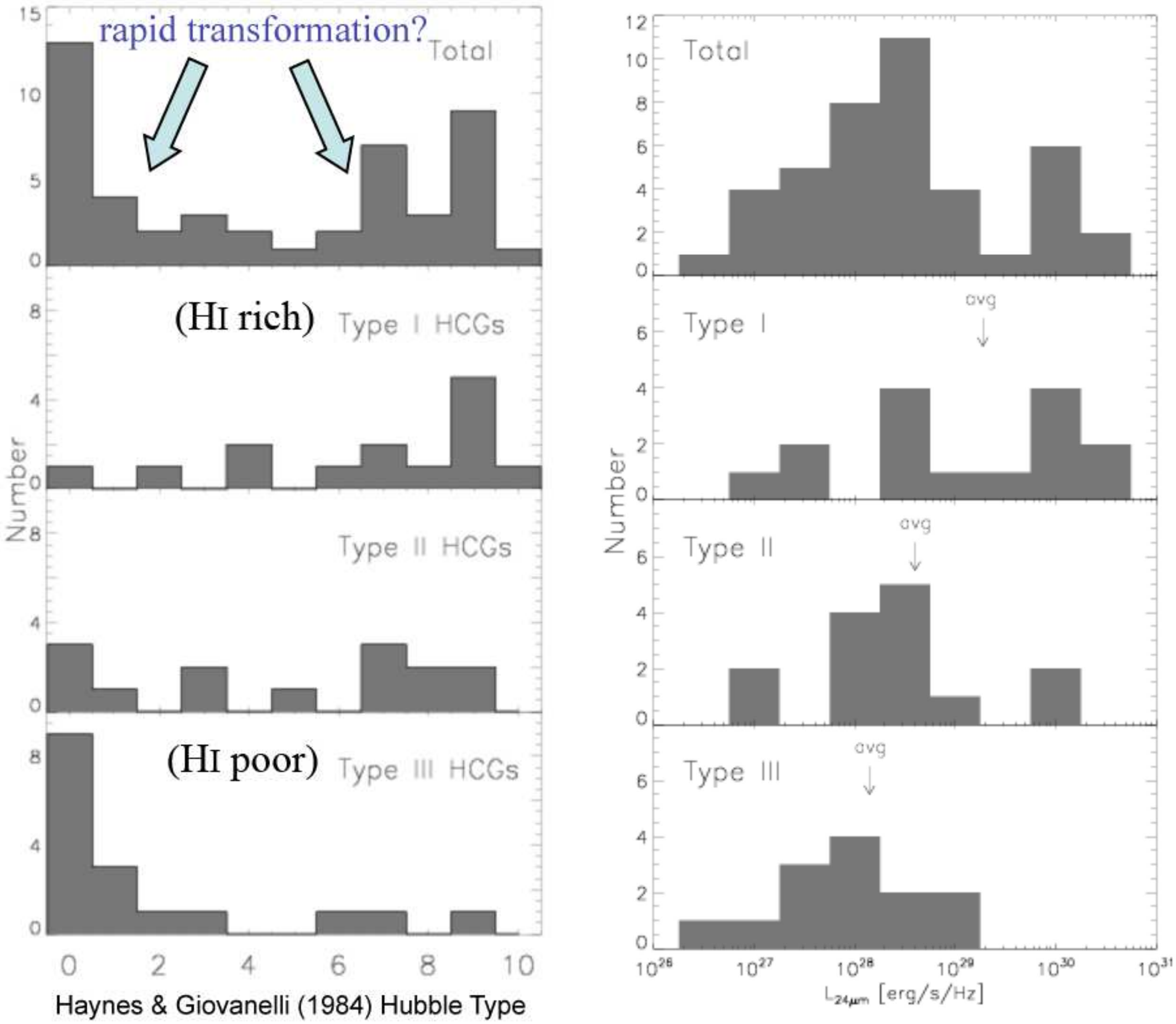

Fig. 2.— **Left panel:** Distribution of Hubble type for member galaxies with respect the HI-richness of the compact group. There is a clear relationship between group type and the morphologies of the constituent galaxies. **right panel:** Histograms of the 24μm luminosities as a function of group type. Not unexpectedly, this result suggests that the most HI-rich groups tend to have the most star formation and/or AGN activity.

A late stage, evolved compact group is represented by HGC 48; Fig 3c, whose bolometric luminosity is dominated by the NIR stellar emission from early-type galaxies, with little or no star-formation present.

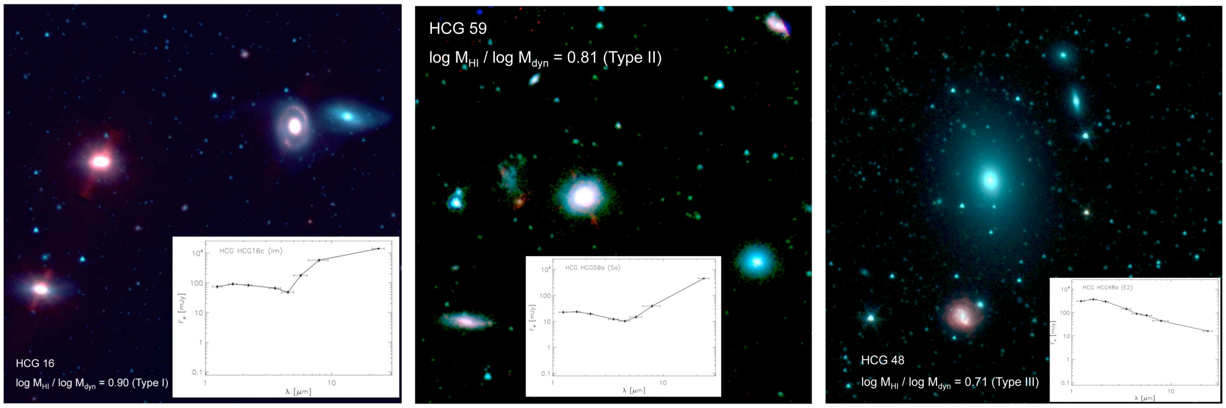

Fig. 3.— **Left:** IRAC 3-color (3.6, 4.5 and 8.0 μm) view of HCG 16, an example of a Type I compact group (HI rich). Note the strong 8μm emission (red) from warm dust and PAH emission bands. The inset shows the NIR-MIR SED for member "C". **Middle:** HCG 59, an example of a Type II compact group. The inset shows the NIR-MIR SED for member "A". **Right:** HCG 48, an example of a Type III (gas poor) compact group. Note the relatively strong stellar emission (blue/green) compared to the ISM emission (red). The inset shows the NIR-MIR SED for member "A".

5. HCG Colors Compared to Field Galaxies

In Fig. 2, the bimodal distribution in the Hubble Type versus HCG Type – H I mass relative to dynamical mass – suggests a rapid transformation from the gas-rich state (right side of plot) to a gas-poor system (left side of plot). If HGCs are undergoing rapid evolution, driven by the extreme physical conditions unique to these systems, then we would expect to observe this delineation with comparison to field galaxies, whose evolution is more quiescent.

Fig. 4 shows the IRAC colors of the HCG galaxies overlaid on the photometry of Spitzer First Look Survey (FLS) galaxies of Lacy et al (2004). The field galaxies are denoted with black points; HGC galaxies are encoded such that purple crosses are Type I (gas rich), red triangles are intermediate, and blue squares are Type III (gas poor). In Fig 4a, the grey shaded region represents the color-color space expected for red AGN and Seyfert-type galaxies. In the lower left the tight cluster of FLS points corresponds to Milky Way stars and galaxies whose light is dominated by stellar photospheric emission. The clustering of FLS sources in the upper left is due to higher redshift galaxies whose 6.2μm PAH feature has shifted into the 8.0μm channel. It is clear that there are both differences between HCG Types and the HCG versus field sample in these color cuts.

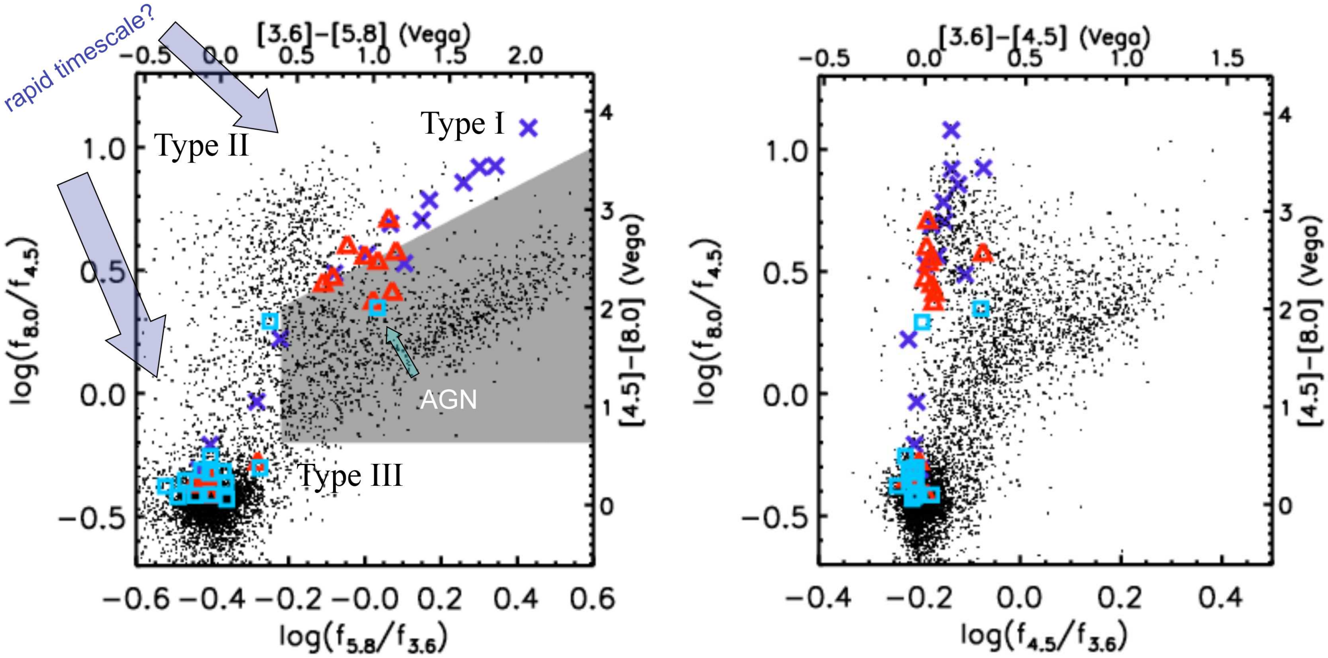

Fig. 4.— **Left:** IRAC color-color diagram. The galaxies in our sample are indicated as purple crosses (relatively HI rich), red triangles (intermediate HI richness), and blue squares (relatively HI poor). The galaxies from the FLS survey (Lacy et al. 04) are shown for comparison. The gray-shaded area indicates the AGN zone. The KISS sample of star-forming galaxies (Rosenberg et al. 2006) tend to lie within the shaded area. **Right:** An alternative color-color scheme that is more sensitive to hot dust and stellar photospheres.

The vertical offset suggests that the HCG galaxies have stronger PAH emission in the 8.0μm band than typical galaxies in the FLS. This could be due to generally elevated star formation and/or dust content in the HGC galaxies, consistent with dynamically triggered star formation, or from the paucity of PAH emission from galaxies with AGN (due to aromatic destruction from the high radiation field). SINGS colors also tend to lie above the FLS sequence. There is curiously little AGN activity in HGC galaxies, they mostly appear to avoid the AGN zone, although one of the Type III galaxies is a known Seyfert and lies close to the Lacy et al (2004) AGN sequence. Similar to the FLS, KISS star-forming field galaxies (Rosenberg et al 2006) also tend to lie in the shaded zone, which again points at a fundamental difference in evolution between HCG galaxies and the field.

Type I and Type II's lie along a tightly constrained track or sequence, consistent with variable contributions from hot dust and PAH emission, which is mostly absent in Type III's;

see also Fig 2b. Our sample of HCGs has a relative lack of galaxies that fall in the color space between systems dominated by stellar light and systems with significant hot dust and /or PAH contributions; unlike field galaxies, there is a clear horizontal gap between the gas-rich (Types I and II) and the gas-poor groups (Type II), again consistent with an elevated state of evolution with dynamical processes taking place on rapid timescales. We note that this horizontal gap is not seen in the (field) galaxies of the SINGS sample (Gallagher et al. 2008; Dale et al. 2005), and thus appears to be a property of HCG evolution.

6. Summary

We present *Spitzer* IRAC/MIPS observations of a sample of 12 Hickson Compact Groups, each typically with ∼4 members, or 45 galaxies in total. We delineate the sample into three types based on the ratio of the group H I mass to dynamical mass, $\log(M_{\mathrm{HI}})/\log(M_{dyn})$. The main results are:

- H I-rich groups are actively forming stars
- H I-poor groups are dominated by stellar photospheric emission from evolved stars
- Rapid evolution of galaxy properties in response to dynamical effects
- Physical/causal connection between global and local properties

As expected, galaxies in the gas-rich groups tend to be the most actively star forming, exhibiting strong PAH and 24μm emission. Our observations also reveal infrared colors that are distinctly different from those seen in field (isolated) galaxies. HCG galaxies exhibit a ”gap” between gas-rich and gas-poor groups in infrared color space that is sparsely populated and not seen in the Spitzer FLS or SINGS sample. This gap may suggest a rapid evolution of galaxy properties in response to long-duration dynamical interactions. These results suggest that the global properties of the groups and the local properties of the galaxies are connected.

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