Hickson Compact Groups:
Galaxy evolution on steroids, a CARMA and Herschel view

Katey Alatalo, Caltech/IPAC
with Phil Appleton (IPAC), Ute Lisenfeld (Granada), Michelle Cluver (AAO), Thodoris Bitsakis (Crete), Emily Freeland (Stockholm), Pierre Guillard (IAS) and Vassilis Charmandaris (Crete).

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Hickson Compact Groups

“By *compact group*, we mean a small, relatively isolated system of typically four or five galaxies in close proximity to one another.”

Hickson 1997 ARA&A 35, 357

- High fraction of E/S0
- Evidence of tidal interactions
- High density, low $\sigma_v$
- Generally deficient in H I
Hickson Compact Groups

Phase 1: low level of interaction

H I is still found in individual galaxy disks

Phase 2: more interaction

H I is disturbed, visible in tidal tails

Phase 3: advanced group stage

H I no longer in individual galaxies. Possibly now outside group or in common envelope

Verdes-Montenegro et al. 2001
HCG: evolutionary cycle

Loose group

HCG: evolutionary cycle

- Compact group
- Loose group

Phase 1

HCG: evolutionary cycle

Loose group → Compact group

Phase 1

H I dispersed

Phase 2

HCG: evolutionary cycle

Loose group → Compact group

Phase 1

Compact group

H I dispersed

Phase 2

Galaxies evolve to E/S0

HCG: evolutionary cycle

- Phase 1: Loose group
- Phase 2: Compact group
- Phase 3: H I dispersed
- Galaxies evolve to E/S0

X-ray gas created

HCG: evolutionary cycle

Loose group → Compact group → H I dispersed

Phase 1

Phase 2

Phase 3

Galaxies evolve to E/S0

X-ray gas created

Field giant elliptical?

HCGs have bimodal IR colors

Color-color plot from Lacy et al. 2004
Lower left: red ETGs
Upper right: blue starformers

HCGs show bimodality between red colors (X) and blue colors (+) with very few in the gap

This gap is not as obvious in underlying population

=> rapid evolution in HCGs

Johnson et al. 2007
MoHEGs

MoHEG = **Molecular Hydrogen Emitting Galaxy**

\[
\frac{H_2}{7.7\mu m\; PAH} \geq 0.04
\]

H\(_2\) emission in MoHEGs is too strong to be energized solely by photon-dominated regions (PDRs).

Cluver et al. (2013) investigated 23 HCGs with Spitzer IRS

14 of those galaxies are considered MoHEGs

Those 14 tend to sit in the IR gap

Ogle et al. 2004

Cluver et al. 2013
HCGs: CO results (30m)

CO in HCGs (in general)

CO/FIR properties “surprisingly similar” to isolated galaxies

20% of HCG spirals appear CO deficient, related to H I deficiency?

25% detection rate of ETGs (same as ATLAS$^3$D; Young et al. 2010)

Verdes-Montenegro et al. 1998
Martinez-Badenes et al. 2012

CO in MoHEGs

CO/FIR properties also similar to isolated galaxies, though $M(H_2)/L_K$ is low

Broad line wings seen in CO of some MoHEGs, higher than can be explained solely with rotation

Lisenfeld et al. 2013, in prep
The complexities of $[\text{C II}]$

$[\text{C II}]$ is a reliable tracer of star formation in normal non-interacting galaxies.

$[\text{C II}]$ traces:
- PDRs
- H II regions and Diffuse neutral/ionized ISM
  - Wolfire 1995, Nakagawa et al. 1998
The complexities of \([\text{C II}]\)

\([\text{C II}]\) is a reliable tracer of star formation in normal non-interacting galaxies.

- **PDRs**

- **H II regions and Diffuse neutral/ionized ISM**
  - Wolfire 1995, Nakagawa et al. 1998

- **X-ray heating?**
  - Appleton et al. 2013

- **Cosmic rays**
  - Nesvadba et al. 2010, Ogle et al. 2010, Appleton et al. 2013

- **Shocks**
  - Appleton et al. 2013, Lesaffre et al. 2013
Shock excitation of [C II]

In normal galaxies, [C II] traces emission associated with SF, and leads to a reliable relation. In turbulent galaxies, this relationship appears to break down.
Fig. 9.— A compilation (Stacey et al. 2010) of the $\text{[C II]} / \text{FIR}$ luminosity versus the FIR luminosity for individual galaxies over a wide range of luminosity and redshift. The SQ PACS regions A-E are also plotted showing the extreme values for the $\text{[C II]} / \text{FIR}$ ratio, especially for the regions less contaminated by star formation (regions B, C and E). Interestingly, those regions exhibiting weak star formation fall closer to the distribution for normal star forming galaxies. The arrow shows a highly schematic mixing line as star formation becomes more dominant over shocks in gas that is actively forming stars rather than in a highly turbulent state.

Fig. 10.— The line luminosity ratio of $\text{[OI]} / \text{[CII]}$ as a function of the far-IR color from a sample of galaxies by (Malhotra et al. 2001) based on ISO data (black points) with the PACS Regions 1-5 for SQ plotted as red filled circles. The solid lines are theoretical models of PDRs based on the models of Kauffman et al. (1999). Unlike the other figures shown in this paper, the SQ points appear to form a continuous distribution at cool color temperatures with the normal galaxies (see text).

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Shock excitation of $\text{[C II]}$

Stephan’s Quintet (HCG 92)

Stephan’s Quintet

Appleton et al. 2006, Cluver et al. 2010, Appleton et al. submitted
Shock excitation of \([\text{C II}]\)

In normal galaxies, \([\text{C II}]\) traces emission associate with SF, and leads to a reliable relation. In turbulent galaxies, this relationship appears to break down.
Herschel [C II] results

Preliminary:
[C II] mom0 mapped for 11 MoHEG systems

9/11 of these systems have also been detected in CO (Lisenfeld et al. in prep)

Spitzer RGB - 3.6, 5.8, 8.0um, respectively. Alatalo et al, in prep
Results: [C II] and CO in HCG 57

HCG 57d brighter in [C II] and bluer in optical than 57a

HCG 57a is the MoHEG
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HCG 57d brighter in [C II] and bluer in optical than 57a

HCG 57a is the MoHEG

HCG 57d is also bright in PAH emission (blue)

HCG 57a is much brighter in CO despite the PAH and [C II] emission in HCG 57d

CARMA recovers 65% of the single dish in HCG 57d, possibly a diffuse molecular component?
Results: [C II] and CO in HCG 57

HCG 57d brighter in [C II] and bluer in optical than 57a
HCG 57a is the MoHEG
HCG 57d is also bright in PAH emission (blue)
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CARMA recovers 65% of the single dish in HCG 57d, possibly a diffuse molecular component?

Clearly, in HCG 57, CO and [C II] do not trace one another (as expected in SFR/PDRs), and HCG 57d has an enhanced [C II]/L_{FIR}.
Results: [C II] and CO in HCG 95

Preliminary (CARMA data arrived last week)
HCG 95c is the MoHEG (H$_2$/PAH = 0.07)
Results: \([\text{C II}]\) and CO in HCG 95

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HCG 95c is the MoHEG (\(\text{H}_2/\text{PAH} = 0.07\))

\([\text{C II}]\) seen in the interacting / tidal tail galaxies
Results: \([\text{C II}]\) and CO in HCG 95

SDSS i r g + [C II]

Spitzer IRAC 3.6 5.8 8.0 + CO

Preliminary (CARMA data arrived last week)

HCG 95c is the MoHEG (\(\text{H}_2/\text{PAH} = 0.07\))

[C II] seen in the interacting / tidal tail galaxies

CO strongest where [C II] strongest, with hints of CO in the tidal tail, and bluest (strong PAH) feature
Summary

HCGs are perfect laboratories to study galaxy evolution

Their H I, and ETG fraction allow for a quick identification along their evolutionary cycle

Galaxy evolution within HCGs is rapid

MoHEG galaxies within HCGs have been shown to be the rare transition objects and appear to be driven by shocks

Herschel [C II] and CARMA CO provide a synergistic dataset to study these MoHEGs
The end

Herschel + CARMA =
The case for resolved maps

Cluver et al. (2013) H$_2$ in HCGs identified interesting sources, but where is the interaction taking place? [C II] can also identify shock-enhanced regions, and Herschel PACS can map (and has mapped 11 HCGs)

Lisenfeld et al. have shown that MoHEGs appear to have normal SF efficiency, but are the sites of shock activity in these MoHEGs also normally forming stars? Comparing CO maps to [C II]/L$_{FIR}$ enhancements shows if shocks lead to inefficiency

Lisenfeld also detected high velocities unexplained by rotation alone. CO maps can identify the sites of the broad wings - be they AGNs (like NGC 1266 or NGC 1377; Alatalo et al. 2011, Aalto et al. 2012) or bow shocks (like SQ, Guillard et al. in prep)

IS [C II] reliably related to SF even in these extreme shock-enhanced systems? [C II] and CO maps can be directly compared, and will allow for a lot of insight into the [C II] emission mechanism. Possibly helping future high-z ALMA [C II] studies normalize their detections.