Dust and Molecular Gas in Early-Type Galaxies

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Outline of talk

- Motivation – For studying gas and dust in ETGs
- Observations – Past, Herschel Space Observatory
- Kinematics – SAMI IFU observations
- Environment – Comparison of GAMA and Virgo
- ALMA – follow-up of 5 dusty ETGs
- KiDS – data and future
- Summary
Motivation for studying gas and dust in ETGs

• Smoking gun of past galaxy evolution – through ISM content, kinematics and structure (e.g. Davis et al. 2011)

• Environmental effects on ISM (e.g. Young et al. 2011; Agius et al. 2015)

• Survivability of dust and dust heating mechanisms

• Gas-to-dust ratios in different galaxy types (cosmological inferences, e.g. Camps et al. 2016)

• ETGs represent endpoints of galaxy evolution? (e.g. Eales et al. 2018)
Multiwaveband data
Elliptical NGC4150

STARS: SDSS (optical)

MOLECULAR GAS: CO (radio)

Crockett et al.
Young et al.

STARS: HST (Opt+UV) Elliptical Galaxy NGC 4150 Hubble Space Telescope WFC3/UVIS
Gas and dust origins in ETGs?

- Stellar mass loss?
- Major or minor mergers?
- Cold gas accretion?

Examples of minor mergers
(van der Voort et al. 2018)
ISM variety in ETGs — e.g. $(M_{\text{HI}}/M_*)$

(Young et al. 2018)
Molecular gas in ETGs

- Previous relations (ATLAS$^3$D, IRAM, CARMA): (Young et al. 2011)
  - ~22% detections, $\log(M(H_2)/M_\odot)=7.1$ to 9.3
  - Lack of $M(H_2)$ versus $M_{gal}$ relations.
  - More CO detected in fast rotating ETGs
  - Most CO gas rich found in rare environments (Davis et al. 2011)
  - Ionized gas follows molecular (CO) gas distribution
  - Kinematic misalignments of CO (& ion) versus stars, particularly in slow rotators:
    - Misalignments indicate external origin

- Simulations: Misaligned gas disks can survive ~2Gyr (van de Voort et al. 2015)
Dust in ETGs

• Earlier results (ATLAS$^3$D (abs), Scuba, ISO (em), Spitzer):
  • 16% dust features in optical images (Krajnovic et al. 2011)
  • Lack of far IR versus optical trend (Temi et al. 2007)
  • Dust detected in 24%(Es), 62%(S0s) in HRS, 62 ETGs (Smith et al. 2012)

• Sample from early H-ATLAS/GAMA (Agius et al. 2013/15):
  • Dust detected in 29% of 771 ETGs
  • Plus Herschel, Virgo cluster survey (HeViCS)
Large surveys

**GAMA**: Galaxy and Mass Assembly Survey (Multi-waveband)

http://www.gama-survey.org/

**H-ATLAS**: Herschel Astrophysical Terahertz Large Area Survey (Sub-mm)

http://www.h-atlas.org/

D.detects dust emission

Good for observing complete samples, e.g. E/S0 galaxies
ETG Study  (Agius, Sansom et al. 2015)

- Out to $z<0.06$, mostly field/group environments
- $(E, S0, Sa)$ from GAMA morphologies (SDSS images; Kelvin et al. 2014)
- H-ATLAS/GAMA – 3 equatorial field areas
- Removed: Contaminants, lenses, AGN, flat, small galaxies, 20 spiral
- 771 ETGs complete down to $M_r = -17.4$ mag ($\approx$SMC)
- 220 submm detections out of 771 ETGs (29%)
- Investigate dust ($M_d, T$) versus:
  - Stellar Mass ($M_*$)
  - Star formation (UV, optical colours, Hα)
  - Types
  - Environment

What trends did we find?...
Downsizing in ETGs

Herschel-ATLAS results (*Agius et al. 2013*)

- Submm detected

![Graph showing downsizing in ETGs]

- log₁₀(M*/M☉)
- NUV-r colour
- (M_r, M_*)
- r_p=-0.58
Kinematics of some ETGs (Bassett et al. 2017)

- 49 out of 220 submm detected ETGs observed with SAMI optical IFU
- Kinematically classified
- Emsellem et al. 2011

\[
\lambda_R = \frac{\sum_{k=1}^{n} F_k R_k |V_k|}{\sum_{k=1}^{n} F_k R_k \sqrt{V_k^2 + \sigma_k^2}}
\]

(n spaxels)

- Only 4 are dispersion-dominated, dusty ETGs
  (\(\sigma > 110 \text{ km/s}; \sigma > V_c\))
Kinematics of some ETGs

- 4 dispersion dominated, dusty ETGs, out of 49 ETGs observed with SAMI
- Measured stars and ionized gas
- Star-to-gas space and kinematic misalignments, suggestive of merger.

(Bassett et al. 2017)
Survival of dust in ETGs

- 49 representative H-ATLAS ETGs - mostly rotation dominated (Bassett et al. 2017)
- Fast rotators have less hot, X-ray gas (e.g. Sarzi et al. 2013)
- Dispersion dominated ETGs ($\sigma > 150$ km/s), with X-ray halos – expect dust destruction in $\tau_{\text{dust}} < 0.02\text{Gyr}$
- Dust is more likely to survive longer in fast rotating ETGs

\(\Rightarrow\) Seen in HRS and H-ATLAS samples

(Sarzi et al. 2013)
Environment densities in sub-mm detected and un-detected ETGs (Agius et al. 2013)

Dusty ETGs tend to lower density environments.

What about denser environments?
Virgo Supercluster region

(1 ly = 0.307 parsecs)
GAMA and Virgo Cluster ETGs

(Agios et al. 2015)
Spectral Energy Distributions + Fitting

\[ \log(\frac{\lambda \lambda L_{\lambda}}{L_\odot}) \]

\[ \chi^2 = 1.20 \]

![Diagram showing spectral energy distributions with data points and spectral ranges labeled GALEX (UV), UBV JHK (Optical), WISE (IR), and Herschel PACS & SPIRE (Sub-mm).]
Comparison with Virgo cluster (Agius et al. 2015)

Specific dust-to-star mass \((\log(M_d/M_*)\) versus Environmental density \((\Sigma_{\text{gal}})\)
Comparison with Virgo Cluster
Lower Dust Masses and Star Formation Rates in ETGs in Virgo Cluster
*(Agius et al. 2015)*

![Graph showing comparisons with Virgo Cluster](image)
Comparison of GAMA with Virgo cluster
(Agius et al. 2015)

H-ATLAS ETGs: 5 targets in yellow observed with ALMA
5 dusty ETGs
(Morphologies from GAMA catalogue)

KiDS (gr)

H-ATLAS (250µm)

1’ × 1’
Resolving dust and gas

- Interferometry $\Rightarrow$ data cube ($x, y, vel$)
- Dust emission - from continuum
- Molecular gas - from line transitions in molecules, $^{12}$CO(2-1) transition at 230 GHz (1.3mm) for low density gas

- Data processing: ALMA calibrations + cleaning + PB corrections (CASA) + moments and spectra (IDL, python).
ALMA continuum detections

- No detections in GAMA64646 and GAMA272990
- Unresolved, faint source at centre of GAMA177186, plus brighter submm source ~4” NW (probably contributed to H-ATLAS fluxes).
- Two serendipitous point sources at ~13” N and W of GAMA622305
- Unresolved source at centre of GAMA622429 – could be AGN.
Dust

• Lack of extended ALMA continuum: LAS and sensitivity limitations (if dust is extended)

• E.g.

![Graph showing predicted and observed ALMA Band 6 results with Scuba2 needed to constrain SED.]

H-ATLAS
PACS & SPIRE

Predicted
Observed
ALMA Band 6

Scuba2
Needed to constrain SED
Results from ALMA (Sansom et al. 2018)
E.g. $^{12}\text{CO}(2-1)$ in GAMA 272990 - an Elliptical galaxy

KiDS optical image (r-band, 1’x1’)  Moment 0 ($^{12}\text{CO}$ flux)  Moment 1 ($^{12}\text{CO}$ velocity)
Molecular gas:
Flux to Luminosity and Mass conversions

• Measure line flux as $S \Delta v$ (Jansky km s$^{-1}$) from spectra:

  $L_{CO} = \left( \frac{c^2}{2k} \right) D_L^2 \{S \Delta v\} \nu_{rest}^{-2}(1+z)^{-1}$

  (K km s$^{-1}$ pc$^2$) (Mpc$^2$) (Jy km s$^{-1}$) (GHz$^{-2}$)

• Conversion from $L_{CO(2-1)}$ to $L_{CO(1-0)}$ (for M-L relation of Solomon et al 1987)
  E.g. Young et al. 2011, 1:1 if same excitation T

• Conversion from CO to H$_2$ mass ($\alpha_{CO}$ or $X_{CO}$)
  Metal dependant, e.g. Remy-Ruyer et al. 2014

• Conversion from $M_{H_2}$ to $M_{Total}$ (for Helium, metals)

\[ M_{Total} = 1.37 \alpha_{CO} \frac{L_{CO(1-0)}}{L_{CO(2-1)}} L_{CO(2-1)} \]
Molecular gas-to-dust mass ratios etc. 

(Sansom et al. 2018)

<table>
<thead>
<tr>
<th>ETG ID</th>
<th>MAGPHYS $M_*$ (M$_\odot$)</th>
<th>MAGPHYS $M_d$ (M$_\odot$)</th>
<th>Estimated $M_*$ $&lt;$ $M_d$</th>
<th>MAGPHYS SFR (M$_\odot$/yr)</th>
<th>ALMA $M_{mol}$ (M$_\odot$)</th>
<th>Estimated $M_{mol} / M_*$</th>
<th>$M_{mol} / M_d$</th>
<th>$t_{depl}$ (yr)</th>
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<td>1.066</td>
<td>3.2E+9</td>
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</tbody>
</table>

$M_{mol} > MWG$
Results from ALMA  *(Sansom et al. 2018)*
Overlays by David Glass (PT PhD student at UCLan)

KiDS optical images (greyscale); $^{12}$CO Moment 0 maps (false colour);
Continuum (green contours)
(17”x17”)

$M_{\text{mol}} \sim \text{few } \times 10^9 \, M_\odot \text{ in 3 ETGs}$
Offset molecular gas in GAMA177186

Moment 0 map around systemic $v_{\text{gal}}$ shows noise, except for offset source. Line emission – but which line? If not CO(2-1) then maybe background galaxy at $z>2$
Future: Kinematic analysis of ALMA CO

GAMA 64646

Software:
KinMS (Davis+13)

Manual tuning of parameters

Empirical arc tan model of exp disk
Examples of information in PV diagrams

**X-structure**
Typical of a bar (disc+ring)
(e.g. van de Voort et al. 2018)

**Ridges**
Typical of spirals
(e.g. Koda et al. 2002)

**Max and min**
Typical of rings
(e.g. Alatalo et al. 2013)
Future: GAMA/KiDS/GalaxyZoo

- KiDS – Kilo Degree Survey with VST
  \textit{(de Jong et al. 2013)}
  
  KiDS improved depth and resolution over SDSS:

- GAMA\_morphs in equatorial fields
  Composite g,r colour KiDS images created by Kelvin et al. (LJMU)
  Decision tree for GZ GAMA-KiDS
  Into Galaxy Zoo (Jan 2017), completed (Feb 2018), \(~50000\) galaxies
  At least 40 attempts per galaxy
  Results reduced and cleaned (Bamford et al.), ongoing bias corrections

- Can we use GZ GAMA-KiDS results to distinguish ETGs (E and S0)?
Sharper Images - Different Classifications

(GAMA64646, KiDS optical 1.1’ x 1.1’ – Galaxy Zoo)

Probabilistic classification
(e.g. Hart et al. 16; Casteels et al. 2013)
Summary

• **H-ATLAS revealed 220 (29%) dusty ETGs in GAMA equatorial fields**
  • Lower mass galaxies more affected (downsizing in ETGs)
  • Mostly green valley galaxies (*see also Kelvin et al. 2018; Eales et al. 2018*)
  • Dust mass correlates poorly with stellar mass
  • In rarer environments

• **49 observed with SAMI**
  • Mostly fast rotators
  • Predict a lack of x-ray halos – hence dust can survive

• **Virgo cluster ETGs** – less dusty

• **ALMA follow-up of 5 dusty ETGs from H-ATLAS/GAMA**
  • None with extended dust (LAS & sensitivity limits)
  • One offset continuum contamination in G177186
  • 3 with massive molecular gas reservoirs \( (M_{\text{Mol}} \sim \text{few} \times 10^9 \, M_\odot) \)
  • Next: KinMS analysis of CO

• **GAMA/KiDS/GalaxyZoo** – morphological possibilities

Thank you