Probing the cold phase ISM in early-type galaxies

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The red sequence is very tight:

**Conclusions:**

- Galaxies exhaust star-forming gas quickly (lack of galaxies in green valley!)
- No ongoing star-formation in the red sequence

ETGs ~ 50% of (SDSS) mass
[Bernardi et al. 2009]
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Meet a early-type galaxy...
Meet a early-type galaxy...

Textbook knowledge:

ETGs:

• “have no axis of rotation”

• “many are pure spheroids”

• “no ISM”

• “no ongoing star-formation”

• “really really boring”
Meet a early-type galaxy...

Textbook knowledge:

ETGs:

• “have no axis of rotation”
• “90% of ETGs rotate!”
  e.g. Emsellem et al., 2011
• “many are spheroids”
• “~90% have imbedded stellar disks!” Krajnovic et al., 2013
• “no ISM”
• “no ongoing star-formation”
• “really really boring”
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The hot ISM

Massive ETGs have large X-ray halos

e.g. O'Sullivan et al., 2001
The hot ISM

Massive ETGs have large X-ray halos

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~70% of ETGs have ionised gas disks

e.g. Sarzi et al., 2006
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The hot ISM

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e.g. Sarzi et al., 2006

The cold ISM

~40% of ETGs have HI reservoirs

e.g. Serra et al., 2011
HI in Early-Type Galaxies

- **40%** of field ETGs detected
  - **<10%** of cluster ETGs

- Detection rate independent of galaxy mass

- HI Masses: **$10^7$ to $10^{10}$** M$\odot$
  - significant fraction of all ETGs as H I-rich as spiral galaxies!
  - ... but typical density is lower

- Majority of HI in disks/rings
- Most dynamically relaxed
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The hot ISM
Massive ETGs have large X-ray halos
- e.g. O'Sullivan et al., 2001

The cold ISM
~40% of ETGs have HI reservoirs
- e.g. Serra et al., 2011

~70% of ETGs have ionised gas disks
- e.g. Sarzi et al., 2006

~23% of ETGs have molecular gas
- e.g. Young et al., 2011
Molecular gas in Early-Type Galaxies

- Detection rate: **22%**
- Molecular gas masses in range $10^7$ to $10^9$ M$_{solar}$
- Molecular gas fractions: 7% to 0.02% ($M_{solar}/L_K$)
- No detections of molecular gas in slow rotators
- Detection rate independent of luminosity!

Detection rate also seems to be independent of environment!

Young et al, 2011
• Detections do not avoid the red sequence
• Mass fractions also don’t depend on optical colour

→ You cannot select galaxies by colour and expect ISM/star-formation free samples!!
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→ You cannot select galaxies by colour and expect ISM/star-formation free samples!!

Even NUV-IR colours cannot be used to select ISM free samples!
(but can help avoid high gas fraction objects)
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- Detections do not avoid the red sequence
- Mass fractions also don’t depend on optical colour
- You cannot select galaxies and expect ISM/star-formation free samples!!
- NUV-IR colours cannot be used to select ISM free samples!
  (but can help avoid high gas fraction objects)

**Big questions:**

- Are these galaxies regenerated?
- Or being quenched?
- Where has the ISM come from?
- Does it form stars normally?

$\rightarrow$ Need interferometry
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CARMA survey- Example Gas Morphologies

- Disks (~55%)
- Bars and Rings (~35%)
- Disturbed Distributions (~10%)

[Davis et al., 2011, 2013, Alatalo et al., 2013]
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Molecular gas in early-type galaxy **NGC4526**

- **0.25” (20 pc!) resolution** CO(2-1) observations with CARMA

- Highest resolution image of molecular gas in an early-type galaxy EVER.
- We resolve the sphere of influence of the black-hole
- Shows importance of resonances/spirals at small scales

*Davis et al., Nature, 2013, 494, 328-330*
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Key Question: What is the origin of the molecular gas?

Two main possibilities:
• Internal stellar mass loss
• External accretion/cooling

Both leave traces in molecular gas kinematics.

Internal stellar mass loss -> gas rotates like stars
External -> gas can rotate in any sense

Use our large statistical sample to see which is dominant:

Davis et al., 2011b
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Key Question: What is the origin of the molecular gas?

- >35% of cold ISM accreted!
- >50% of ISM accreted in the field galaxies!
- Cluster objects have aligned ISM (ISM not accreted, or relaxed?)
- High mass objects have aligned ISM (suppressed accretion in high mass objects?)

Davis et al., 2011b
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Atomic gas chemistry

**PACS** \([\text{C} \ II], [\text{O} \ I] 63 \ \mu m, [\text{NII}] 122 \ \mu m\) for 20 galaxies

**SPIRE FTS** for 9 galaxies

R. Lapham/L. Young et al., in prep
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Atomic gas chemistry

FIR line ratios in early-type galaxies are broadly similar to those in spirals.

Also: $[\text{C II}]/\text{FIR}$ vs $\text{FIR}/\text{H}_2$ consistent with “normal” galaxies -- Gracia-Carpio et al 2011

R. Lapham/L. Young et al., in prep
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Atomic gas chemistry

But... ATLAS$^{3D}$ galaxies have systematically lower [O I] 63 / [C II].
Atomic gas chemistry

- the high [N II]122/[C II] galaxies are all Virgo Cluster members;
- they are also HI-deficient (Serra et al 2012; Lucero & Young 2013)
- M(H$_2$)/M(H I) >80
- [N II]205 also strong

- stripping of diffuse atomic gas in the intracluster medium?

- BUT compare observations of the central galaxies of cooling flow clusters (Edge et al 2010; Mittal et al 2011, 2012)

R. Lapham/L. Young et al., in prep
Molecular chemistry

- **12CO, 13CO, HCN, HCO+** Crocker et al 2012;
- **CS, CH$_3$OH** – Davis et al., 2013b
- **CO J=3-2** Bayet et al 2012;
- chemical network modeling with specific applications to early-type galaxies
  - enhanced cosmic ray ionization
  - high metallicity, $\alpha$-enhanced abundances

(Bayet et al 2012)
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Star formation - (Davis et al, in prep)

- ETGs form stars less efficiently than spirals!
- SFE lower by a factor ~2.5!

Could this effect be driven by different physical conditions in the ISM? (Deep potential, harsh irradiation, high metallicity, alpha-enhancements, high shear...)

\[ \Sigma_{\text{HI+H}_2} \quad \rightarrow \quad \Sigma_{\text{FUV+22 \mu m,corr}} \quad \rightarrow \quad \text{Gas Density (HI+H}_2 \ – \ WSRT+CARMA} \]
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Star formation - (Davis et al, in prep)

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$\rightarrow$ Gas Density (HI+H2 – WSRT+CARMA) $\rightarrow$
(caution! Xco... systems are high metallicity however...)
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Star formation - (Davis et al, in prep)

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↑ SFR density (GALEX+WISE 22um) → Gas Density (HI+H2 – WSRT+CARMA) →
(caution! Xco... systems are high metallicity however...)
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Star formation - (Davis et al, in prep)

H owever:

- ETGs form the same amount of stars per unit dynamical time as spirals/starbursts/high-z objects!
- Global dynamic star-formation regulation?
- Or simply a manifestation of a local dynamical model? (c.f. Krumholtz, Dekel, McKee 2012)
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Conclusions

• Early type galaxies can have complex, multi-phase ISMs!
  → Hot, warm and cold gas detected, dust also present in large quantities

• Much of the gas is accreted
  → What happens to stellar mass loss?!

• Environment has a strong effect on the morphology, kinematics and chemistry of the ISM

• Star formation efficiencies low in early-type galaxies
  → Star formation appears to be dynamically regulated
Thanks for Listening!

Any questions?
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