The GOGREEN survey

Rethinking satellite galaxy quenching

Michael Balogh
Jan 2021

http://gogreensurvey.ca/
## The GOGREEN team

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Michael Balogh</td>
<td>Waterloo (PI)</td>
</tr>
<tr>
<td>Kristi Webb, PhD</td>
<td></td>
</tr>
<tr>
<td>Andrew Reeves, PhD</td>
<td></td>
</tr>
<tr>
<td>Karen McNab, MSc</td>
<td></td>
</tr>
<tr>
<td>Matthew Pereira Wilson</td>
<td></td>
</tr>
<tr>
<td>Adam Muzzin, York</td>
<td></td>
</tr>
<tr>
<td>Gregory Rudnick, Kansas</td>
<td></td>
</tr>
<tr>
<td>Gillian Wilson, UC Riverside</td>
<td></td>
</tr>
<tr>
<td>Andrea Alonso, Cordoba</td>
<td></td>
</tr>
<tr>
<td>Pierluigi Civiano, Trieste</td>
<td></td>
</tr>
<tr>
<td>Pierluigi Cerulo, Concepcion</td>
<td></td>
</tr>
<tr>
<td>Jeffrey Chan, UC Riverside</td>
<td></td>
</tr>
<tr>
<td>Kevin Cooke, Kansas</td>
<td></td>
</tr>
<tr>
<td>Michael Cooper, UC Irvine</td>
<td></td>
</tr>
<tr>
<td>Gabriella De Lucia, Trieste</td>
<td></td>
</tr>
<tr>
<td>Ricardo Demarco, Concepcion</td>
<td></td>
</tr>
<tr>
<td>Alexis Finoguenov, Helsinki</td>
<td></td>
</tr>
<tr>
<td>Ben Forrest, UCR</td>
<td></td>
</tr>
<tr>
<td>David Gilbank</td>
<td></td>
</tr>
<tr>
<td>Pascale Jablonka, EPFL</td>
<td></td>
</tr>
<tr>
<td>Kristen Jones, Kansas</td>
<td></td>
</tr>
<tr>
<td>Egidius Kukstas, Liverpool JM</td>
<td></td>
</tr>
<tr>
<td>Joel Leja, Harvard CfA</td>
<td></td>
</tr>
<tr>
<td>Chris Lidman, ANU</td>
<td></td>
</tr>
<tr>
<td>Ian McCarthy, Liverpool JM</td>
<td></td>
</tr>
<tr>
<td>Sean McGhee, Birmingham</td>
<td></td>
</tr>
<tr>
<td>Hernan Muriel, Cordoba</td>
<td></td>
</tr>
<tr>
<td>Julie Nantais, Andrés Bello</td>
<td></td>
</tr>
<tr>
<td>Allison Noble, ASU</td>
<td></td>
</tr>
<tr>
<td>Lyndsay Old, ESA</td>
<td></td>
</tr>
<tr>
<td>Irene Pintos-Castro, Toronto</td>
<td></td>
</tr>
<tr>
<td>Bianca Poggianti, INAF/Padova</td>
<td></td>
</tr>
<tr>
<td>Heath Shipley, McGill</td>
<td></td>
</tr>
<tr>
<td>Remco van der Burg, ESO</td>
<td></td>
</tr>
<tr>
<td>Benedetta Vulcani, INAF/Padova</td>
<td></td>
</tr>
<tr>
<td>Howard Yee, Toronto</td>
<td></td>
</tr>
<tr>
<td>Dennis Zaritsky, Arizona</td>
<td></td>
</tr>
</tbody>
</table>

Bob Abraham, Toronto; Richard Bower, Durham; Charlie Conroy, CfA Harvard; Warrick Couch, AAO; Erica Ellingson, Boulder; Henk Hoekstra, Leiden; Mark David Lacy, NRAO; Diego Garcia Lambas, Cordoba; Matt Owers, AAO; Laura Parker, McMaster; Alessandro Rettura, JPL; Ian Smail, Durham; Jason Surace, Caltech IPAC; Jeremy Tinker, NYU; Carlos Valotto, Cordoba; Tracy Webb, McGill; Andrew Wetzel, UC Davis; Jon Willis, Victoria

with help from:
- Callum Bellhouse, INAF/Padova
- Kevin Boak, Waterloo
- Anna Davidson, Kansas
- Nicole Drakos, UCSC
- Sean Fillingham, U Washington
- Caelan Golledge, Kansas
- Stephen Gwyn, NRC/CADC
- Grayson Petter, Kansas
- Melinda Townsend, Kansas

http://gogreensurvey.ca/
Why study Galaxy clusters?

- Rich environments with many galaxies at the same distance.
- Nearly all baryons directly observable
- Cosmologically sensitive
- Examples of extreme environments and rare processes
- Mass and baryon accretion history reasonably well understood from theory


http://gogreensurvey.ca/
Galaxies that are satellites of a more massive host halo are more likely to be quenched. i.e. SFR history depends on the large scale environment.

A satellite galaxy loses its source of fresh gas from cosmological accretion. Many of the other complex physical processes (e.g. SFR, feedback) are likely unaffected.

Adapted from Hirschmann+2014
Galaxies in clusters are more likely to be quenched

No shortage of ideas:
- Ram pressure stripping
- Merging/harassment
- Tidal stripping

...but theoretical models consistently overpredict the number of quenched satellites
GOGREEN and GCLASS

GCLASS (Muzzin et al. 2012)
- Spectroscopic survey of 10 rich clusters at $0.86 < z < 1.34$
- High spectroscopic completeness, ~500 members
- 222-hour project from 2009-2012
- with Gemini/GMOS (8 allocations)

GCLASS (Muzzin et al. 2012)
- Spectroscopic survey of 10 rich clusters at $0.86 < z < 1.34$
- High spectroscopic completeness, ~500 members
- 222-hour project from 2009-2012
- with Gemini/GMOS (8 allocations)

GCLASS (Muzzin et al. 2012)
- Spectroscopic survey of 10 rich clusters at $0.86 < z < 1.34$
- High spectroscopic completeness, ~500 members
- 222-hour project from 2009-2012
- with Gemini/GMOS (8 allocations)

GCLASS (Muzzin et al. 2012)
- Spectroscopic survey of 10 rich clusters at $0.86 < z < 1.34$
- High spectroscopic completeness, ~500 members
- 222-hour project from 2009-2012
- with Gemini/GMOS (8 allocations)

GCLASS (Muzzin et al. 2012)
- Spectroscopic survey of 10 rich clusters at $0.86 < z < 1.34$
- High spectroscopic completeness, ~500 members
- 222-hour project from 2009-2012
- with Gemini/GMOS (8 allocations)
Cluster member
Non-member

Wide wavelength range of photometry

Rest-frame optical spectroscopy

SPTCL-0546
z=1.067

HST F160W
First results

2. Stellar mass functions in clusters (van der Burg et al. 2020 A&A, 638, 112)

In Preparation
- critical assessment of environmental trends in cosmological hydrodynamical simulations at $z \approx 1$ (Egidius Kukstas et al.)
- The role of halo mass in environmental quenching at $z = 1$ (Andrew Reeves et al.)
- The morphology of quenched cluster galaxies in GOGREEN (Jeffrey Chan et al.)
- Transition galaxies in GOGREEN (Karen McNab et al.)
- Dynamics and mass profiles of clusters at 0.8<$z<$1.5 (Andrea Biviano et al.)
- AGN abundance (Pintos-Castro et al.)

Featured in this talk
Stellar mass functions

Precise SMF for $M_* > 10^{9.5} M_\odot$

van der Burg et al. (2020)
Chan et al., 2019
High fraction of quenched galaxies

\[ QFE = \frac{Q_{\text{cluster}} - Q_{\text{field}}}{1 - Q_{\text{field}}} \]

Environmental quenching is even more effective at \( z = 1 \) than at \( z = 0 \)

Depends on stellar mass – unlike at \( z = 0 \)

See also Muzzin et al. (2012); Balogh et al. (2016)
Stellar mass function of quiescent galaxies in clusters is identical to that in the field; in stark contrast from what is observed locally.

Baldry et al. (2006)
Quiescent galaxy ages

We use MCMC to build posteriors for the SFH parameters, and several parameters which control for shape distortions and systematic biases in the data.

The median age of cluster quiescent galaxies is only 0.3 Gyr older than that of field quiescent galaxies.
Simulations do not reproduce mass-dependence of satellite quenching

Hydrangea and MACSIS to provide more massive clusters with the same physics

Kukstas et al. in prep
Conclusions and takeaway points

Clusters at 1<z<1.5 show a large excess of quenched galaxies at all stellar masses $M_*>10^{9.5}M_\odot$

- Stellar mass function of these galaxies is identical to that of field galaxies: requires a similar mass-dependent quenching
- Ages do not admit a large “head start”. Need more quenching in protocluster environments, but not earlier

The evolution of satellite galaxies, especially at z>1, can be an important test for models. Difficult to get right
