Title: The Red-Sequence Cluster Survey and its Applications to Cosmology

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Abstract: The Red-Sequence Cluster Survey (RCS2) is a 1000-square-degree, multi-color imaging survey carried out using MegaCam on the 3.6m CFHT which is optimized for the search of galaxy clusters with $0.15 < z < 1.0$ using the red-sequence method. Designed to create a well-characterized, large sample of clusters, the survey has the main goals of constraining cosmological parameters, studying galaxy cluster evolution, and discovering a large sample of strong gravitational lenses. I will give a summary of the current status of the RCS2 survey and discuss preliminary results on cosmological parameter fitting. I will present some initial results from an extension of the RCS method to Spitzer IRAC images from the SWIRE database to search for galaxy clusters in the "cluster desert" redshift range of $1 < z < 2$ will also be shown.
The **Red-Sequence Cluster Survey**

Howard Yee
University of Toronto
Dept. of Astronomy & Astrophysics

& The RCS1/RCS2 collaboration
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The RCS1/2 Collaboration:

Howard Yee (U. Toronto);
Mike Gladders (U. Chicago)

D. Gilbank (U. Waterloo), H. Hoekstra (Leiden),
E. Ellingson (U. Colorada), R. Yan (U. Toronto),
B.C. Hsieh (ASIAA, Taiwan), S. Majumdar (Tata Inst., India),
T. Webb (McGill), A. Muzzin (Yale),
I.H. Li (Swinburne, Australia), K. Blindert (MPIA),
F. Barrientos (U. Catolica, Chile), A. Hicks (Michigan St.),
P. Hall (YorkU), M. Bautz (MIT), Lihwai Lin (ASIAA, Taiwan)

+ a number of students and postdocs and others at Chicago, UVic, McGill, NCU, NTU, ASIAA, York, CITA,
Outline:
- a summary of the RCS:
  the red-sequence method
  the RCS1 and 2
- cosmological parameters from RCS1
- RCS2 strong lensing arcs
- The HST Cluster Supernova Survey
- The SpARCS survey: finding clusters at z>1
Scientific motivations for galaxy cluster surveys:

1. Growth of structures; the measurement of cosmological parameters.
2. Galaxy evolution and cluster physics: effects of environment, large scale structure
3. Using galaxy cluster potential as gravitational lens “telescope”.
What is needed for a modern galaxy cluster survey:

- large area ($10^2$ to $10^3$ sq deg)
- redshift to $>\sim 1$
- well-understood selection effects and completeness
- characterization of the sample:
  redshift and mass [or more practically: mass proxy]

Cluster survey methods:
1. Optical/IR  (most efficient!)
2. Sunyeav-Zeldovich effect
3. X-ray

(Approximately factors of 10 different in cost!)
Optical Search for Clusters

Coma
(A1656, z=0.025)

Richness~ Abell 2

NOAO 0.9m, Lopez-Cruz & Yee

PDCS, z=0.83
Modern Optical/IR Surveys for Galaxy Clusters:

- New large areal digital detectors (both optical [~1 sq deg] and IR [~1/10 sq deg])

- New cluster search techniques using multiple filters, overcoming most of the projection problems
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The Cluster Red-Sequence Method


Uses the early-type (red) galaxies as markers for cluster detection

Requires only 2 filters: extremely efficient!
Color-magnitude relation as a function of redshift

RCS

Color

Magnitude
Az=0.89 RCS cluster

galaxies in color slice
(of z=0.9 ellipticals)

all galaxies
A $z=0.89$ RCS cluster

**galaxies in color slice**
(of $z=0.9$ ellipticals)

**all galaxies**
THE CORE OF THE CLUSTER CANDIDATE
CRS 1620+2929 + SURROUNDING LARGE
SCALE STRUCTURE AT REDSHIFT 1

A z=0.89 RCS cluster

galaxies in color slice
(of z=0.9 ellipticals)

all galaxies
Galaxy density in different red-sequence slices (Real data from RCS1)
Galaxy density in different red-sequence slices (Real data from RCS1)
Galaxy density in different red-sequence slices
(Real data from RCS1)
Color

Magnitude

RCS

\( (R_{\text{c}} - T_{\text{eb}}) \)

\( (N - T_{\text{eb}}) \)

1.4

0.5

1.4

0.5
Red-sequence photo-$z$ (2 filters) vs spectral $z$:
RCS1: $\Delta z \sim 0.03$ to 0.06;
RCS2: $\Delta z \sim 0.015$
Red-sequence photo-z (z filters) vs spectral z:
RCS1: $\Delta z \sim 0.03$ to 0.06;
RCS2: $\Delta z \sim 0.015$
The RCS1

- 92 sq deg, 1998-2001
- total: 13 nights CFHT (12k), 17 nights CTIO (Mosaic Cam)
  (including lost times)
- R, z’ bands: 15-25 min exposures
  1/3 sq deg per pointing
  Typical depth (5 sigma): z’~23.6, R~24.8
- 22 patches (typically 2.5x2.5 deg), distributed over RA & dec
RCS2:  www.RCS2.org

A ~1000 sq deg cluster survey, with a $z \sim 1$ limit

- a Canada/Taiwan collaboration
- CFHT MegaCam

Three filters: $z'$ $r'$ $g'$ + $i'$ (from CFH-QS)
exposure times: 6 8 4 min 5

5σ limits: 23.2 25.0 25.4 (AB magnitude)

Expected completeness depth:
~$2 \times 10^{14}$ $M_{\odot}$ clusters at $z \sim 1$

Yee et al. 2007, astro-ph/0701839
**Main Science Goals: (RCS2)**
- Constrain cosmological parameters $\Omega_m$, $\sigma_8$, and $w$
- Create a sample of $\sim$150 strong arc lenses
- Cluster evolution
- Weak lensing, cosmic shear (wide/shallow)
- A very large sample of photo-$z$
  (useful $0.1 < z < 0.7$)

**Cluster sample:**
- Optimized for $z \sim 0.1$ to 1.0;
Total number of clusters (useful for cosmology) expected: $\sim 15,000 (>\sim 10^{14}$)
CFHT MegaCam

36 2k x 4.5k chips,
325M pixels

one image ~ 750Mb

0.18”/pix

field~ 1 sq deg
CFHT MegaCam

36 2k x 4.5k chips, 325M pixels
one image ~ 750Mb
0.18”/pix
field~ 1 sq deg
Observing completed Jan 2008:

- total 920 sq deg:
  770 sq deg + 150 sq deg from CFHLS-Wide

- photometry (120 million objects) mostly completed,
- preliminary cluster catalogs generated

The most massive cluster in RCS2 (so far):

\[ z=0.70, \ -5 \times 10^{15} \ M_{\text{sun}} \]
Cosmology with Clusters Counts:

Number of clusters $N(z)$ per unit $z$ and angular area

$$\frac{dN(z)}{dz d\Omega} = \frac{dV}{dz d\Omega} n(z) = \frac{c}{H(z)} d_A^2 (1 + z)^2 \int_0^\infty dM f(M) \frac{dn(M,z)}{dM}$$

$f(M)$ links the “mass observable” to the mass

Determination of $\Omega_m$ and $\sigma_8$ from RCS1 (72 sq deg):
Mass Observables:

Examples: \( T_x, L_x, \text{SZ flux}, \text{optical/IR richness or light} \)

- Mass observable used for the RCS:
  
  optical richness \( B_{gc} \) (galaxy-cluster correlation amplitude:
  
  \[ \xi(r) = B_{gc} r^{-\gamma} \]
  
  net number of galaxies scaled by LF and spatial distribution;


  also see Yee & Ellingson 2003)

Mass - observable relation

\[
M = A_{B_{gc}} B_{gc}^{\alpha} (1 + z)^{\gamma}
\]
CNOCl + RCS1 weak lensing
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Examples: $T_x$, $L_x$, SZ flux, optical/IR richness or light

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Mass - observable relation

\[ M = A_{Bgc} B_{gc}^\alpha (1 + z)^\gamma \]

use self-calibration method

(Majumdar & Mohr 2001)
RCS1 Cosmological Results:


Use Marko-Chain Monte Carlo fitting to Jenkin mass function; (Subha Majumdar)
RCS1: 7-parameter fit; ~1000 clusters

$\Omega_m, \sigma_8,$

$h$ (WMAP prior)

$n_s$ (WMAP prior)

+ 3 cluster parameters

linking richness to mass: $M = A_{Bgc} B^{\alpha}_{gc} (1 + z)\gamma$

$([A, \alpha]=M_{\text{lim}}, \gamma, +\text{scatter})$

(+ $\Omega_{\text{tot}}=1$)
## Priors in MCMC Analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_m$</td>
<td>0.05–0.55</td>
<td>Uniform</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>0.40–1.30</td>
<td>Uniform</td>
</tr>
<tr>
<td>$h$</td>
<td>0.72 ± 0.08</td>
<td>Gaussian</td>
</tr>
<tr>
<td>$\Omega_b$</td>
<td>0.046</td>
<td>Fixed</td>
</tr>
<tr>
<td>$n$</td>
<td>0.99</td>
<td>Fixed</td>
</tr>
<tr>
<td>$A_{Bgc}$</td>
<td>6–14</td>
<td>Uniform</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0–3</td>
<td>Uniform</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>-4 to 4</td>
<td>Uniform</td>
</tr>
<tr>
<td>$f_{sc}$</td>
<td>0–1</td>
<td>Uniform</td>
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Cluster counts vs redshift

![Graph showing cluster counts vs redshift](image)
\[ \Omega_m = 0.31 \pm 0.10 \]
\[ \sigma_8 = 0.67 \pm 0.17 \]

consistent with
WMAP year 3/5 results:
**Derived Parameters from the Self-Calibration Analysis without Mass-Richness Priors**

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</tr>
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<td>$\log (M_{\text{vir}})$</td>
<td>$14.61^{+0.82}_{-0.70}$</td>
</tr>
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<td>$\gamma$</td>
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<td>$\Omega_m$</td>
<td>$0.30^{+0.12}_{-0.11}$</td>
<td>$0.31^{+0.11}_{-0.10}$</td>
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<tr>
<td>$\sigma_8$</td>
<td>$0.70^{+0.27}_{-0.15}$</td>
<td>$0.68^{+0.22}_{-0.14}$</td>
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<tr>
<td>$A_{BGC}$</td>
<td>$9.61 \pm 0.65$</td>
<td>$10.27^{+1.37}_{-0.66}$</td>
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</tr>
<tr>
<td>$\alpha$</td>
<td>$1.92 \pm 0.24$</td>
<td>$1.70 \pm 0.24$</td>
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</tr>
<tr>
<td>$\gamma$</td>
<td>$0.81^{+1.91}_{-1.66}$</td>
<td>$0.64^{+1.96}_{-1.90}$</td>
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<tr>
<td>$f_{\text{sc}}$</td>
<td>$0.69 \pm 0.20$</td>
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\(^a\) For the case with no priors, parameter values are as reported in Table 2, with values of $A_{BGC}$ and $\alpha$ as reported in the text ($A_{BGC} = 10.55^{+2.27}_{-1.71}$ and $\alpha = 1.64^{+0.91}_{-0.90}$).
Effects of scatter on the mass observable relation
RCS: cluster parameters
(red: derived from self-calibration; blue: measured from CNOC1)

\[ M = A_{bgc} B_{gc}^{\alpha} (1 + z)^{\gamma} \]

\[
\log(A_{bgc}) = 10.55 +/- 1.5 \\
(z=0.3) \quad (10.05 +/- 0.89)
\]

\[
\alpha = 1.64 +/- 0.79 \\
(1.58 +/- 0.27)
\]

\[
\gamma = 0.40 +/- 2.5
\]

scatter: 0.73 +/- 0.17
(0.65, RCS Blindert et al)

CNOC1,
Yee & Ellingson 2003
Chandra X-ray observation of 0.7>z>1.1 RCS clusters

Hicks et al. 2008
arXiv:0710.5513);
13 0.7<z<1.1 clusters
Discovery of a
Large scale structure at high-z

(Gilbank et al. 2008, ApJL, ;
Magellan IMACS spectroscopy
one mask, ~420 redshifts
field size: 27’; ~13 Mpc at z~0.9
the 3 clusters span ~6 Mpc

blue dots: z~0.9
black dots: “field”
red circles: X-ray positions
contour/gray scale: z=0.9 red sequence galaxy density

Additional IMACS spectroscopy (3500+ elts)
Gas mass fraction ($f_{\text{gas}}$) in clusters

- **Pink**: RCS clusters (0.65<z<1.1)
- **Blue**: CNOC1 clusters (0.15<z<0.55)

Is there an evolution of $f_{\text{gas}}$ (~factor of 2) between $z\sim0.35$ to $z\sim0.85$?
- Implications for X-ray and SZ cluster surveys
Gas mass fraction ($f_{\text{gas}}$) in clusters

- **Pink**: RCS clusters
  
  \(0.65 < z < 1.1\)

- **Blue**: CNOC1 clusters
  
  \(0.15 < z < 0.55\)

Is there an evolution of $f_{\text{gas}}$ (~factor of 2) between $z \sim 0.35$ to $z \sim 0.85$?

- Implications for X-ray and SZ cluster surveys
RCS-2: Strong Lensing Samples

Gladders et al.

~80 systems so far
(~450 sq deg)
RCS-2: Strong Lensing Samples

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Galaxy lenses
RCS-2: Strong Lensing Samples

Galaxy lenses
RCS-2: Strong Lensing Samples

Galaxy lenses
Nature's Telescope


$z=3.8$
Cluster Strong Lenses, with “bright” arcs

In the next decade the number of known cluster strong lenses will be in the thousands...
Similar Project in SDSS – here's recent color mosaic of some lenses (mostly SDSS, but pretty!)
Searching for RCS-2 Lensing Directly

• Search of 330 square degrees yields several hundred candidates
• Cutting on \( r_E > 5'' \) and I/w > 10, yields 27 distinct cluster lenses; (actual current number is \( \sim 40 \) including prior partial search results)
• Total expected number is \( \sim 75 \) cluster lenses under the strict criteria above;

* total number of lenses, including many at 1''-5'' \( r_E \), is in the hundreds
The most remarkable example: massive clusters: RCS2327

Einstein radius: 50”

Cluster Redshift: 0.6995

Source Redshift: 2.98
Velocity Disp. of Abs. Line Members of RCS2-2327.4-0204

Absorption Line Galaxies Only: Gauss. Fit: 1407 km sec⁻¹

Abs. Line: 187 members
Emission Line: 80 members
Post-Starburst: 16 members
AGN: 4 members

 Velocity dispersion
1400 km/sec

Mvir ≈ 3 × 10¹⁵ Msun

Preliminary x-ray temperature 9.5 keV
RCS-2 Arc Counts, Lens Redshift Distribution

(base on predictions from Hennawi et al. 2007)
Caveats:
g-band versus r-band selection
surface brightness limits
However...
Statistics of Einstein radius

Raw Arc Counts: * RCS-2  
* CFHT-LS  
* SDSS

CFHT-LS: 28 sq deg, Cabanac et al 2007;  
RCS: 329 sq deg;  
SDSS: ~9000 sq deg (direct search)
Note on source redshift: average $z \sim 1.5$ from those with spectro-$z$

$u$-band image: very few drop-outs ($<5\%$ with $z>3$)
RCS-2 Cosmological Implications

- Total number of arcs is sensitive to cosmology, due to effects principally on total number of lenses, as well as concentration, sub-structure, etc.

- Current RCS-2 results are in decent agreement with relatively recent predictions for arc counts with redshift, and this comparison is NOT systematic dominated; generally a higher sigma-8 is preferred, but...

- similar results obtained by Fedeli et al. 2009 (astro-ph/0803.0656)
Follow-up: Cluster Masses

• Cluster dynamics being studied using GISMO as well as using ancillary slits in arc-targeted MOS observations at the VLT and Gemini telescopes

• Data are in hand for 28 systems; GISMO observations (21 clusters so far) yield 25-100 cluster members per mask;

• simple analysis confirms every system studied to date as a massive cluster: $\sigma_v$ ranges from 600 - 1300 km/sec

• SZA observations underway of the largest lenses – eventually targeting several dozen systems
The HST Cluster SN Survey

(PI: S. Perlmutter; paper I: Dawson K. et al, submitted to AJ)

- a new strategy for high-z SNe: search in fields of z-1 clusters for SNe in E galaxies

Advantages:
- significantly less dust in E, compared to Sp
- higher yield rate due to the presence of a cluster
- can target specific (high) redshift

- 219 orbits (188 ACS discovery, 31 Nicmos follow-up)

- 25 clusters, z-0.9 to 1.4; 10 clusters from the RCS
Total of 37 SNe discovered

10 SNe in clusters
(out of 21 with $z > 0.9$: an increase of 90%)

6 out of 10 SNe in ellipticals (an increase of 150% in SNe in E’s)
SNe in E’s reduce dispersion by a factor of 4.
one SN in E is worth ~16 SNe in Sp!

High-z clusters are valuable for SNe cosmology
The Search for $z > 1$ Clusters

- better discrimination for cosmological parameters;
BUT: many fewer clusters;
very difficult to calibrate mass observables

- provide crucial target fields for SNe (especially in early-type galaxies)
at $z > 1$
- the RCS technique is optimized when the 2 filters straddle the 4000Å break
- requires IR images for $z > 1.1$
- the cluster redshift “desert”: $1.3 < z < 2$
- the RCS technique is optimized when the 2 filters straddle the 4000A break
  - requires IR images for $z > -1.1$
  - the cluster redshift “desert”: $1.3 < z < 2$

**The SpARC survey** (Adam Muzzin, G. Wilson, Yee, +...)
(The Spitzer Adaptation of Red-Cluster Sequence)
- combining Spitzer SWIRE 3.6μm data (50 sq deg) with deep $z'$ band (-2hr integration)
- CFHT (8 nights) + CTIO (15 nights); 6 patches
  -- search for clusters to $z - 1.8$

  -- ~200 clusters with $z > 1$;
  - currently a core sample of 10 being followed-up intensely with: MOS, multi-band imaging, X-ray...
Final area: 42 deg$^2$

SpARCS ELAISN2-109

Gemini/GMOS N&S spectroscopy
SpARCS ELAISN2-109

19 high-confidence members

$z = 1.18$

Gemini/GMOS N&S spectroscopy
SpARCS ELAISN2-109
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SpARCS ELAISN2-109

19 high-confidence members

$z = 1.18$

$z = 1.1796$

$\sigma = 700 \pm 200$ km/s
RCS-2 Arc Counts, Lens Redshift Distribution

(base on predictions from Hennawi et al.)