Optical/IR Surveys for High Redshift Galaxy Clusters:

(Recent Results from the RCS)

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Scientific objectives for cluster surveys:

1. Growth of structures: the measurement of cosmological parameters and cluster formation.


3. Using galaxy clusters potential as gravitational lens “telescopes”
Growth of Structure and Cosmology

- The mass function, \( N(M,z) \), is sensitive to cosmology via:
  a) the cosmological volume effect
  b) the growth of structure

Can be used to measure:
\( \Omega_m, \sigma_8, w(z) \)
Error ellipses for:

1. Supernovae: 200, 400
2. CMB: MAP, Planck
3. Cluster mass function – 1000 sq deg, $z_{\text{end}} = 1.2$, $T_x < 5 \text{keV}$
4. Joint error ellipse: 200 SNe+MAP+clusters

What is needed for a modern galaxy cluster survey:

- large area ($10^2$ to $10^3$ sq deg)
- redshift to $\gtrsim 1$
- well understood selection effects and completeness
- characterization of the sample (e.g., redshift, mass, [or richness, $T_x$], ....)
- sample deep enough down the mass function
  (reducing effects of mass-observable scatter; for studying cluster formation and evolution)

Cluster survey methods:
1. Optical/IR
2. X-ray
3. Sunyeav-Zeldovich effect
Coma (A1656, $z=0.025$)

Richness~ Abell 2

NOAO 0.9m, Lopez-Cruz & Yee
PDCS 0223+0423, $z=0.84$

Postman, Lubin, Oke

“Match-filter” technique, single filter
A New Generation of Optical 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 (e.g., the cluster red-sequence technique).
The Cluster Red-sequence Method


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

Requires only 2 filters: Inexpensive
A z=0.89 RCS cluster (of z=0.9 ellipticals)
galaxies in color slice
all galaxies

THE CORE OF THE CLUSTER CANDIDATE
CRS 1620+2929 + SURROUNDING LARGE
SCALE STRUCTURE AT REDSHIFT 1
Color-magnitude relation as a function of redshift

Requirements:
- filters straddling the 4000 Å break,
- deep enough to cover 1 to 2 mag below M*,
- large enough area to find rich clusters (~1 to 2/sq deg)
The Red-Sequence Cluster Survey (RCS)
The RCS1/2 Collaboration:

Howard Yee (Toronto); Mike Gladders (Carnegie/Chicago)

Toronto: D. Gilbank, K. Blindert, I-hui Li, A. Muzzin
U. Victoria: H. Hoekstra
P.U. Catolica, Chile: F. Barrientos, P. Infante
U. of Colorado: E. Ellingson, M. Hicks, Y.S. Loh,
  A. Bender
Taiwan: P. Hsieh (ASIAA), W. Ip (NCU),
  S.Y. Wang (ASIAA), T. Chieuh (NTU)
CITA: S. Majumdar,
Leiden/McGill: T. Webb
MIT: M. Bautz
  + others in York U., Waterloo, MacMaster, Michigan State
The RCS1

- 100 sq deg, (actual: 92 sq deg, 1998-2001)
- total: 13 nights CFHT, 17 nights CTIO (including lost times)

- R, z’ bands: CFHT -- CFH12K: 15 min R, 20 min z’
  CTIO -- Mosaic-II Cam: 20 min R, 25 min z’
  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 and Dec.
RCS2:

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

Mini-consortium:
Canada (Univ. of Toronto, UVic, CITA; +US: OCIW, U.Colorado; +Others)
Taiwan (COSPA; ASIAA/NTU/NCU)

Three filters: $z'$  $r'$  $g'$  (SDSS)
exposure $t$:  6   8   4  min

5σ limits: 23.2  25.0  25.4  (AB magnitude)
Expected completeness/depth:
750 km/s (5 kev) clusters at $z \sim 1$

CFHT MegaCam:
CFHT MegaCam

36 2k x 4.5k chips, 325M pixels
one image ~ 750Mb
0.18”/pix
field~ 1 sq deg
~12 patches of 9x9 or 6x6 deg$^2$, most patches near declination=0 for follow-up access from both hemispheres

-- total time required: 43 nights (280hrs, 830 sq deg)  
  +170 sq deg from CFH-LS Wide
- 3-band photometry for ~100 millions galaxies, 
  ~20000 to 30000 clusters (0.1<z<1.0) down to sub-Abell 0 richness (~10$^{14}$ M$_{\text{sun}}$)

Major Science Goals:
- measure w (~0.1 alone; 0.05 combined with SNe,CMB)
- obtain 50-100 strong lensing clusters
- galaxy cluster evolution
Current Status of RCS2: (Oct 05)

- 252 sq deg collected
- expect ~350 sq deg by Jan 06
- expected completion: 2007A
Follow-up Programs

(1) To calibrate mass observables
(2) Study cluster evolution, dynamics

1. Spectroscopy:
   - multi-object spectroscopy: CFHT MOS, Gemini GMOS, VLT FORS2, Magellan (LDSS2, IMACS, LDSS3)
Example redshift histograms
Red-sequence photo-z (2 filters) vs spectral z
2. X-Ray Observations

- Chandra data for 12 clusters (z~0.9)
- XMM proposals
3. Multi-Color Imaging/Photo-z

(Theses: Paul Hsieh, I-Hui Li)

- B V (+ R z’) imaging of 34 sq deg of CFHT RCS1 patches
- photo-z for 1 million galaxies
- CTIO 4m z’RBV for RCS core sample

  Yee et al. 2005 ApJL, 629, L77 (galaxy color evolution)
  I-Hui Li: galaxy groups in clusters, in field.
3. IR Imaging

- Dupont 2.5m:
  K-band imaging of $\sim 100 \ z \sim 1$ clusters +
  companion deep I-band (Magellan MagicCam)
  H-band imaging of $\sim 150 \ 0.3<z<0.8$ clusters (Muzzin thesis)
- SPITZER: IRAC images (3.6/4.5um) for 40 RCS
  core clusters.
4. HST ACS Imaging

- HST snapshot program (75 cluster sample, \(0.3<z<0.9\))
- HST high-z elliptical galaxy SNe program (PI: Perlmetter)
  - 9 RCS1/2 \(z\sim1\) clusters, deep stacked images
HST $z \sim 1$ cluster SNe program (PI: Perlmutter)
SN in RCS 0221, cluster early-type galaxy, confirmed $z = 1.02$
5. **SZ**

- 6 z~0.9 clusters observed with OVRO, all detected (K. Dawson/Carlstrom group)
- new pointed observation program with RCS2 sample

RCS0224-0025

- SCUBA 850um images for 8 z~1 clusters
- SCUBA2 high-z RCS2 survey planned (2006B)
- Deep VLA images (so far 4 high-z clusters)
Galaxy Evolution:
The Butcher-Oemler Effect
Is there a Butcher-Oemler effect?


CNOC1, Ellingson et al, 2001
- ~2000 RCS1 clusters, 0.45<z<0.90
- ensemble clusters in 4 redshift bins,
- z’-band selection;
- k-corrections based on observed colors

BO effect from RCS1 clusters

Loh, et al., 2005
$R-z' \text{ vs } z'$ CDM, ensemble cluster (0.55<z<0.65)
Fitting color histogram

- $0.45 < z < 0.55$
- $0.50 \text{ of } r/r_{200}$
- *Red Fraction: 0.933*

- $0.65 < z < 0.75$
- $0.50 \text{ of } r/r_{200}$
- *Red Fraction: 0.703*

- $0.85 < z < 0.90$
- $0.50 \text{ of } r/r_{200}$
- *Red Fraction: 0.452*
BO effect (expressed as red-fraction) as a function of cluster-centric radius. $f_{\text{red}}$ determined by fitting the red side of the color distribution.
Cosmology with Clusters: \( \Omega_m \) and \( \sigma_8 \) from RCS 1

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

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

\( f(M) \) links the “mass observable” to the mass
Mass Observables:

Examples: $T_x$, $L_x$, SZ flux, optical/IR richness or light


\[ \xi(r) = B_{gc} r^{-\gamma} \]

Mass - observable relation

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

\[ M = A_{BgC} B_{BgC}^\alpha (1 + z)^\gamma \]
Two Approaches:

1. Measure the observable-mass relation (as a function of redshift).

2. Self-Calibration method
   (Majumdar & Mohr, 2003)
   - simultaneously fit the cluster parameters
   - require a large sample (>~1000 clusters), and the existence of a well-behaved and tractable scaling relation
The Magic of Self-Calibration:

- Self-calibration can take care of the evolution of the mass-observable.
- Self-calibration can absorb many “sins” in the data:
  - e.g., any systematic that changes with redshift can be absorbed into the factor $(1+z)\gamma$;
  - e.g., incompleteness with $z$, systematics in Bgc, etc.

However, knowledge in the mass-observable relation will always provide better constraints.
The Data:

- RCS1: 75 sq deg, $B_{gc} < 300$ (sub Abell 0, $\sim 450$km/s)
  Redshift range: $0.3 < z < 0.9$;
  $\sim 1100$ clusters;
  use $B_{gc(\text{red})}$: computed from red sequence galaxies
    (more stable)
(Demonstration) Cosmological Results:

Use Marko-Chain Monte Carlo fitting to Jenkin mass function (Subha Majumdar)

RCS1: 7-parameter fit:

\[ \Omega_m, \sigma_8, \]

\[ h \ (\text{WMAP prior}) \]

\[ n_s \ (\text{WMAP prior}) \]

+ 3 cluster parameters

linking richness to mass

\[ (+ \Omega_{\text{tot}}=1) \]

(Gladders, Yee, Majumdar, Hoekstra, Barrientos, Infante, Hall, 2005, to be submitted to ApJL)
\( \Omega_m = 0.343 \pm 0.064 \)

\( \sigma_8 = 1.05 \pm 0.14 \)

consistent with WMAP

Cluster parameters:
RCS: cluster parameters

( red: derived from self-calibration; blue: measured from CNOC1)

\[ \log(A_{\text{Bgc}}) = 10.95 \pm 0.78 \]
(\[ z=0.3 \])(10.05 \pm 0.89)

\[ \alpha = 1.64 \pm 0.28 \]
(1.58 \pm 0.27)

\[ \gamma = 0.28 \pm 0.35 \]
(-0.5 \pm 0.5)

Blue: results from CNOC1, 

Hicks et al 2005
SPT survey forecasts (Majumdar & Cox 2005):

\[ \frac{dn}{dz} \text{ of 22000 clusters} \]

\[ + \]

Independent mass determination of 100 clusters with 30% mass uncertainty.

\[ \Delta \Omega_m = 0.018 \]
\[ \Delta \sigma_8 = 0.039 \]
\[ \Delta w_0 = 0.018 \]
\[ \Delta w_a = 0.585 \]
\[ \Delta \log(A_{SZ}) = 0.281 \]
\[ \Delta \alpha = 0.020 \]
\[ \Delta \gamma = 0.168 \]
RCS Mass-Observable Calibration:

- Primary calibration: weak lensing mass.

Three redshift regimes:

1. $z < 0.5$
   - Ensemble clusters from survey data themselves
   - + single clusters from RCS1 HST snapshot program.

2. $0.5 < z < 0.8$
   - Ensemble clusters from CFHT-LS-wide
   - + single clusters from RCS1 HST snapshot program

3. $0.8 < z < 1.1$ : HST SNe stacked images (9 clusters)
More mass-observable calibrations:

- X-ray: Important as a cross check, and at $z>0.8$, where lensing observation is difficult.
- Dynamical mass

**Allow for cross-calibrations**

**Conversely:**

If we know cosmology really well, the self-calibration method can be used to learn about cluster scaling relations.
Opt/Ir searches for Redshift >1

- require IR searches
- provides more leverage for w, but fewer clusters, more difficult to calibrate mass observable

- e.g., combining SWIRE 3.6um data (50 sq deg) with z’ band -- search for clusters to z ~ 1.8
a $z=1.25$ cluster from a pilot SWIRE $z'-3.6\text{um}$ search: composite color image (Muzzin et al.)
Gravitational Lensing

RCS2319, Magellan Magic-Cam,
cluster $z = 0.93$, arc $z = 3.8$

RCS0224, HST
cluster $z = 0.77$, red arc $z = 4.89$

Gladders, Yee, & Ellingson, 2002, AJ, 123, 1
Examples of strong arcs discovered in RCS2

g’-band images, 4min
RCS2 strong arc cluster, z~0.7, Magellan LDDS3 images, 4’x4’ i, r, g
Summary:
- The optical/IR red-sequence method (and its variants) is a power and efficient method for creating well-characterized samples of cluster galaxies covering up to $z \sim 1$, and potentially to $z \sim 2$.
- The key to using a large cluster sample for cosmology is the availability and calibration of an inexpensive mass observable (e.g., cluster richness vs mass)
- The RCS1 sample demonstrates that clusters as a probe for cosmology is tractable, and potentially very powerful