Optical/IR Surveys for High-Redshift Galaxy Clusters

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What I will talk about:

- Why high redshift clusters
- Optical/IR cluster finding techniques, a brief history  
  the red-sequence method and variants
- Modern high-redshift optical/IR cluster surveys  
  RCS1, RCS2, IRAC Shallow Survey, SpARCS
- some scientific results:
  - a determination of $\Omega_m$, $\sigma_8$
  - Chandra-X-ray obs. of RCS clusters
  - a supercluster at $z=0$
  - the evolution of z’ band cluster galaxy LF ($z\sim0.3-1$)
1. Growth of structures: the measurement of cosmological parameters: $\Omega_m$, $\sigma_8$, $w$

2. Galaxy evolution and cluster physics: effects of environment

3. Using galaxy clusters potential as gravitational lens “telescopes”.

Scientific motivation for galaxy cluster surveys:
$\Lambda$CDM, $\Omega m=0.3$
A Brief History of Cluster Surveys

Herschel 400 -- red= spiral nebulae
A Brief History of Cluster Surveys

- criteria: \( \geq 50 \) galaxies within \( m_3 \) to \( m_3 + 2 \)
  within radius of \( 1.7'/z \), (about 2Mpc), where \( z \) is estimated by eye (\( z < 0.2 \))
- used Palomar Optical Sky Survey plates
- cataloged a total of 2717 clusters, with 1683 satisfying above
- divided clusters into Abell richness classes

<table>
<thead>
<tr>
<th>( N_{Abell} )</th>
<th>Abell 0</th>
<th>Abell 1</th>
<th>Abell 2</th>
<th>Abell 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>( \sim 1000 )</td>
<td>1224</td>
<td>383</td>
<td>6</td>
</tr>
<tr>
<td>( \sigma ) ( \text{km s}^{-1} )</td>
<td>600</td>
<td>750</td>
<td>950</td>
<td>1250</td>
</tr>
<tr>
<td>Mass ( (10^{14} M_\odot) )</td>
<td>2</td>
<td>4</td>
<td>9</td>
<td>15</td>
</tr>
</tbody>
</table>
Zwicky: same data, but different method: isopleth >50 galaxies within contour @2x background

Some later photographic surveys:
- GOH (1986, Palomar Schmidt+5m plates) attempt to find high-z clusters
- UK Schmidt
  - APM (1992)
    - 4300 sq deg, digitized images
    - 240 clusters (≥ Abell 1)

First digital CCD imaging survey:
- PDCS (1996; Postman, Oke, Lubin);
  - Palomar 5m CCD drift scan; 5.1 sq deg, V=24
  - “matched filter” technique;
  - 75 clusters, 0.2<z<1.2
The LCDCS:
another early attempt for high z clusters
- Gonzalez, Zaritsky et al. 2001
- 130 sq deg, Swope 1m drift scans
- 1073 clusters, $0.3 < z < 1.0$; 30% false detections
Best-known nearby rich cluster

Coma (A1656, z=.025)

Richness~ Abell 2

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

Postman, Lubin, Oke

“Match-filter” technique, single filter
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
2. X-ray
3. Sunyeav-Zeldovich effect
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

Low-z example: SDSS
The Cluster Red-Sequence Method


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

Requires only 2 filters: Inexpensive
Color-magnitude relation as a function of redshift

![Diagram showing color-magnitude relation with redshift as the parameter. The diagram includes two plots for different color-magnitude relations, with redshift values ranging from 0.5 to 1.4.](image)
Red-sequence photo-z (2 filters) vs spectral z (RCS1 data);

Δz \approx 0.04 \text{ to } 0.08
Simulated R-band field with a z=1, Abell richness 1 cluster embedded
A z=0.89 RCS cluster

The core of the cluster candidate CRS 1620+2929 + surrounding large scale structure at redshift 1

Galaxies in color slice (of z=0.9 ellipticals)

All galaxies
Galaxy density in different red-sequence slices (Real data from RCS1)
The RCS1/2 Collaboration:

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

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

+ others and students and postdocs at Chicago, UVic,
McGill, CITA, York, Waterloo, MIT, Michigan, NCU, ASIAA
The RCS1

- 92 sq deg, 1998-2001
- total: 13 nights CFHT, 17 nights CTIO (including lost times)
- R, z' bands: 15-25 min exposure
  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.

Main Science Goals: (RCS1)
Measure $\Omega_m$ and $\sigma_8$
cluster evolution

optimized for $z \sim 0.4$ to 1.0;
usable range: $z \sim 0.25$ to 1.3

Total number of clusters cataloged: $\sim 8000$ (3$\sigma$ cut)
RCS2: www.RCS2.org

A ~1000 sq deg Cluster survey, with a z ~1 limit

CFHT MegaCam (Canada/Taiwan)
~800 sq deg + 150 sq deg from CFHT-LS wide

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~1

CFHT MegaCam:
CFHT MegaCam

36 2k x 4.5k chips, 325M pixels
one image ~ 750Mb
0.18”/pix
field~ 1 sq deg
Main Science Goals: (RCS2)

- Measure eqn of state of dark energy, \( w = \frac{P}{\rho} \) (to \( \sim 0.15 \)), \( \Omega_m \) (to \( \sim 0.03 \)), and \( \sigma_8 \) (to \( \sim 0.05 \))
- create a sample of \( \sim 100 \) strong lenses
- cluster evolution
- weak lensing (wide/shallow)
- photo-z (3/4–color) \( \sim 10–30 \times 10^6 \) (useful) galaxies

optimized for \( z \sim 0.1 \) to 1.0;
Total number of clusters (useful for cosmology) expected: \( \sim 20,000 \)
Strong lensing in RCS2 clusters
Chandra X-ray obs of $0.7 > z > 1.1$ RCS clusters

Hicks et al. 2007
13 $0.7 < z < 1.1$ clusters
Gas mass fraction in clusters

- 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
Cosmology with Clusters:

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
Mass Observables:

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

- Mass observable used for the RCS:
  optical richness $B_{gc}$ (galaxy-cluster correlation amplitude:
  net number of galaxies scaled by LF and spatial distribution;

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

Mass - observable relation

\[ M = A_{Bgc} B_{gc}^\alpha (1 + z)^\gamma \]
RCS1 Cosmological Results:


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

RCS1: 7- parameter fit; ~1000 clusters

\[ \Omega_m, \sigma_8, \quad \frac{dN(z)}{d\Omega} = \frac{dV}{dz} n(z) = \frac{c}{H(z)} d_z^2 (1+z)^2 \int_0^\infty dM f(M) \frac{dn(M,z)}{dM} \]

h (WMAP prior)

n_s (WMAP prior)

+ 3 cluster parameters linking optical richness to mass: \[ M = A_{Bg} B_{gc}^{\alpha} (1+z)^y \]

(3 parameters \( M_{lim} = f(A, \alpha), \gamma, \text{scatter} \))

(+ assume \( \Omega_{tot} = 1 \))
\[ \Omega_m = 0.31 +/- 0.10 \]
\[ \sigma_8 = 0.67 +/- 0.17 \]
consistent with WMAP year 3 result:
\[ \Omega_m = 0.24 - 0.27 \]
\[ \sigma_8 = 0.72 - 0.77 \]
Cluster parameters are consistent with CNOC1 calibration
Mapping a Large scale structure at high-z

Chandra X-ray image

Red-sequence galaxy density, $z=0.9$ slice
Supercluster RCS2319

composite
CFHT z’Rg;
Chandra X-ray (pink)
Magellan IMACS spectroscopy
one mask, ~420 redshifts
field size: 27'; ~20Mpc at z~0.9
the 3 clusters span ~7 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 slits)
planned for Oct 2007
Cluster Galaxy Luminosity Function

I. RCS1 z’ band galaxy LF


z’ vs R-z’ CMDs of stacked clusters, background subtracted

500 clusters, 30,000 red sequence galaxies

0.35<z<0.95
Red sequence LF ($z'_{AB}$)

black dashed-lines: $z=0.4$ LF evolved passively
The build-up of the faint end LF of the red galaxies is consistent with having the blue cloud galaxies moving up to the red-sequence with decreasing redshift: “down-sizing” interpretation of galaxy formation/evolution.
The Search for z >1 Clusters

- at z>2.5: a “cluster” of Ly Break galaxies a proto-cluster? (Steidel et al, 2006)

- the cluster redshift “desert”: 1.3<z<2
The Search for $z > 1$ Clusters

- the cluster redshift "desert": $1.3 < z < 2$
- provides more leverage for $w$,
  (but, fewer clusters, and much more
difficult to calibrate mass-observables).
- transition between "proto-clusters"
  and clusters
- the multi-color technique requires
  IR images for $z > \sim 1.2$
- most efficient:
  combining Spitzer 3.6μm with
  optical data
The IRAC Shallow Survey
(Eisenhardt et al, 2004)
8.5 sq deg in NOAO DWFS Bootes field

- use optical-IRAC photo-z to find clusters
Stanford et al (2006) cluster at $z=1.41$
The SpARCS survey
(A Muzzin, G. Wilson, +....)

- combining publicly Spitzer SWIRE 3.6μm data with 2hr integration optical z’ band (CFHT 8 nights/ CTIO 15 nights);
  z’_AB ~24.2 (5 sigma)
- 4 patches, totaling 50 sq deg
  -- search for clusters to z~1.8
Current area: Reduced, 22/48 deg$^2$
In hand, 44/48 deg$^2$
SpARCS ELAISN2-109

$z_{\text{phot}} = 1.25$
New Cluster Candidates at $z > 1$

19 high-confidence members

$z = 1.18$

$\sigma = 700 \pm 200$ km/s
SpARCS ELAISN2-117

$z_{\text{phot}} = 1.3$
New Cluster Candidates at $z > 1$

33 high-confidence members
$z = 1.20$

Gemini/GMOS N&S spectroscopy
$z = 1.1960$
$\sigma = 650 \pm 150$ km/s

$z = 1.1960$
$\sigma = 650 \pm 150$ km/s
10 Hr on-sky N&S mask with GMOS-S

10 High confidence members, 
$z = 1.34$
### Current spectroscopically confirmed high-z clusters

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<th>Most distant X-ray clusters</th>
<th>Most distant IR clusters</th>
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<tr>
<td>$z = 1.45$, XMMXCS J2215.9-1738</td>
<td>$z = 1.41$, ISCS J143809+3414</td>
</tr>
<tr>
<td>$z = 1.39$, XMMU J2235.3-2557</td>
<td>$z = 1.34$, SpARCS J0035.7-4312</td>
</tr>
<tr>
<td>$z = 1.27$, RDCS J0849+4452</td>
<td>$z = 1.24$, ISCS J1434.5+3427</td>
</tr>
<tr>
<td>$z = 1.24$, RDCS J1252.9-2927</td>
<td>$z = 1.20$, SpARCS J1638.8+4039</td>
</tr>
<tr>
<td>$z = 1.22$, XLSS J022303-043622</td>
<td>$z = 1.18$, SpARCS J1634.5+4021</td>
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Spitzer has nearly doubled the number of known distant clusters in just a few years!
Future Surveys that can be used for the search of high-z clusters:

Talks on Thursday!
- Pan-STARRS, DES, LSST, WISE, NIRSS
- 500 sq deg Spitzer warm mission survey (to be proposed)
Summary:
- The optical/IR red-sequence method (and its variants) is a powerful and efficient method for creating well-characterized samples of cluster galaxies covering up to $z \sim 1$, and potentially to $z \sim 2$.
- The RCS1 sample demonstrates that clusters as a probe for cosmology is tractable, and potentially very powerful.
- Large samples of clusters covering a good redshift and richness range will provide significant advances in the study of the evolution of clusters and cluster galaxies.