A Census of Baryons in Groups and Clusters

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Baryons and Structure Evolution

relationships among baryons, dark matter timely

galactic structure due to baryon packing, star formation efficiency (Zaritsky’s colloquium!)

clusters are baryon sinks, ~Universal baryon fraction

cosmology:  1) stars & gas ---> cluster mass ---> number density & spatial distribution, 2) mass fraction in cluster baryons ---> small-scale CMB anisotropies ---> power spectrum normalization, 3) baryon fraction(z) ---> dark energy (!)

galaxy evolution: efficiencies of star formation, feedback, enrichment
Intracluster Stars and Structure Evolution

Intracluster stars hard to count, but significant

trace potential, enrich cluster gas, solve missing baryons, constrain star formation efficiency

arise in groups?
Intracluster Stars and Structure Evolution

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Detection of Intracluster Starlight

**uniform data:** drift scans in Gunn-I for 24 clusters, groups at $z = 0.03-0.13$

**optimized reduction:** removal of stars, galaxies, saturated stars, sky gradients $>>$ intracluster stellar component

**2-D modeling:** convolution with PSF, multiple components, model/data masking (GALFIT; Peng et al. 2002)

**goal:** robust profiles to 300 kpc ($\sim 26$ mag/sq’’
Detection of Intracluster Starlight (cont.)

first-pass sky removal    smoothed image

co-add image
Detection of Intracluster Starlight (cont.)

- Co-add image
- Fit saturated stars
- Star map
- Smoothed image
Detection of Intracluster Starlight (cont.)

- co-add image
- fit saturated stars
- subtract PSFs

subtracted image
smoothed image
Detection of Intracluster Starlight (cont.)

- background image
- smoothed image
- co-add image
- fit saturated stars
- subtract PSFs
- fit large-scale sky gradients
Detection of Intracluster Starlight (cont.)

- co-add image
- fit saturated stars
- subtract PSFs
- fit large-scale sky gradients
- subtract background map

subtracted image
smoothed image
Detection of Intracluster Starlight (cont.)

- final masked image
- smoothed image
- co-add image
- fit saturated stars
- subtract PSFs
- fit large-scale sky gradients
- subtract background map
- mask objects
Detection of Intracluster Starlight (cont.)

Final Data Quality

Initial sky level: \( \mu_I \approx 20 \, \text{mag/sq''} \)

5σ detection: \( \mu_I \approx 27.5 \, \text{mag/sq''} \)

Equivalent physical radius: \( r \approx 200-600 \, h_{70}^{-1} \, \text{kpc} \)
Detection of Intracluster Starlight (cont.)

2-D fit with single deV profile poor at large $R$

fails on ellipticity and position angle profiles

Gonzalez, Zabludoff, & Zaritsky 2005

single deV ($r^{1/4}$)
Detection of Intracluster Starlight (cont.)

2-D fit with single Sersic profile better

fails on ellipticity and position angle profiles

Gonzalez, Zabludoff, & Zaritsky 2005

Abell 2571

single Sersic \( r^{1/n} \)
Detection of Intracluster Starlight (cont.)

two component model
best fit

not random view of triaxial system

dbl deV \left( 2r^{1/4} \right)
Properties of Intracluster Starlight: Luminosity, Orientation, Size, Ellipticity

80-90% of light of two components

Gonzalez, Zabludoff, & Zaritsky 2005
Properties of Intracluster Starlight: Luminosity, Orientation, Size, Ellipticity

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aligned within 10 deg

~40% of time
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10-40x brightest cluster galaxy (BCG), ~cluster halo
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10-40x brightest cluster galaxy (BCG), ~cluster halo
flatter than BCG, like cluster galaxies

Gonzalez, Zabludoff, & Zaritsky 2005
Properties of Intracluster Starlight: Mass Profiles

velocity dispersion rises

stars trace galaxy, then cluster potential
Properties of Intracluster Starlight: Mass Profiles (cont.)

Kelson et al. 2002

tracers within critical 100 kpc
distinguish among mass profiles

NFW profiles

DM dominates
Properties of Intracluster Starlight: Mass Profiles (cont.)

isotropy, $M/L \Rightarrow$ soft core like
X-ray, strong lensing, not like sims

but what is scatter?
Mass Profiles (cont.)

Kelson et al., in prep.
Mass Profiles (cont.)

Kelson et al., in prep.

A2877

A3376

A496

Projected radius (kpc)

Velocity (km/s)

Velocity dispersion (km/s)
Mass Profiles (cont.)

A496

Kelson et al., in prep.

another soft core

$\sigma$ (km/s)

$R$ (kpc)

projected radius (kpc)
Properties of Intracluster Starlight: Color Gradients

gradients smooth, same over mass range => dynamically relaxed

colors also like old population

suggest metal-poor progenitors

early formation, not much recent growth?
Properties of Intracluster Starlight: Summary

- distinct, ubiquitous

- 80-90% of two components (40% of all light within $r_{500}$)

- aligned with BCG, but exceptions

- 10-40x bigger than BCG, ~cluster halo

- more elliptical than BCG, ~cluster members

- responds to cluster potential (dispersion rises)

- dynamically-relaxed, old stars, metal-poor progenitors $\Rightarrow$ formed early, growth slowed
Enrichment of Intracluster Medium

$[\text{Fe/H}] \sim 0.3$ solar hard via galactic winds,

but intracluster stars deposit all their metals

evolve old population ($= L_{ICL}$), SNe and Fe at $z$, integrate over $z$
Enrichment of Intracluster Medium (cont.)

~30% of Fe within $r_{500}$

need galaxies + intracluster stars, but 85% metal loss?

Sivanandam et al. 2008
Enrichment of Intracluster Medium (cont.)

~30% of Fe within $r_{500}$ need galaxies + intracluster stars, but 85% metal loss?

SN Ia rate upper-bound gives 35% metal loss

can now account for all Fe

what about trend? SN Ia rate change with environment?
Baryon Budget of Clusters

Gonzalez, Zaritsky, & Zabludoff 2007

baryon fraction \sim WMAP

classic from groups to clusters

no undetected component

gas up, stars down \implies star formation efficiency down
Apportionment of Cluster Stellar Baryons

Gonzalez, Zaritsky, & Zabludoff 2007

intracluster stars rise slower than galactic stars
Apportionment of Cluster Stellar Baryons (cont.)

Gonzalez, Zaritsky, & Zabludoff 2007

- intracluster stars rise slower than galactic stars
- fewer intracluster stars, more galactic stars $\implies$ less efficient stripping?
- selection effects?
- intracluster stars do not need cluster
Conclusions

intracluster starlight: distinct, significant, tracer of cluster potential, old

intracluster metals: from stars in and out of galaxies

baryon fraction: ~Universe, constant with mass

baryon phases: more gas, fewer stars vs. mass (star formation efficiency);

fewer intracluster stars, more galactic stars vs. mass (early formation, growth via stripping stalled)
Properties of Intracluster Starlight: Fundamental Manifold

velocity dispersion profiles rise, do not reach cluster value
Properties of Intracluster Starlight: Fundamental Manifold

velocity dispersion profiles rise, do not reach cluster value

for cluster velocity dispersion, intracluster stars on F-M

==> trace cluster potential

AIZ with Gonzalez & Zaritsky

intracluster light

E,S

dE,dSph

ultra-compact dwarfs

$2 \log V - \log I_e = \log T_e - 0.8$