Observations of the Intra-Cluster Light

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Outline

1. Observations of ICL in clusters – A review
2. ICL from deep photometry
3. Observational obstacles
4. Brightest Cluster Galaxies and ICL in clusters
5. Specific energies: using planetary nebulae as tracers of light components
6. Conclusions

The Age of Heroes (1951 – 1988)

Credit: J.J. Feldmeier
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Struble (1988) – A 545
Davies et al. (1989) – A1367
Uson et al. (1991a; 1991b) – A2029, 910, 1413, 1763, 2218
Scheick et al. (1994) – A2670
Vilchez-Gomez (1994) – A2390, Cl 1613+31
Tyson et al. (1995; 1998) – A1689, Cl 0024+1654
Boughn et al. (1997) – A115, 403, 2397

Abell 2029 (Uson et al. 1991)
ICL from deep photometry

- Core of the Coma cluster:
  Photographic photometry
  Thuan & Kormendy 1977

- Abell 4010 (left, z=0.096)
  Abell 3888 (center, z=0.151)
  Deep CCD photometry
  Krick & Bernstein 2007
  Abell 1914 (right)
  Feldmeier+2004

See also Melnick+’77, Bernstein ’95, Feldmeier+’04, Gonzalez+’05, Mihos+’05, Krick+’06
ICL from deep photometry cont.


SDSS with stacking methods (Zibetti et al. 2005)
HST at intermediate redshifts in the Frontier Field and CLASH (Montes Trujillo 2014, 2015; DeMaio + 2015, Burke+2015, Morishita+2017)

HSC at intermediate redshifts (Huang et al. 2017)
ICL properties in individual clusters

- ICL surface brightness profile shape varies between clusters - Krick & Bernstein+07 & Huang+17
- Ellipticity generally increases with radius, position angle sometimes has sharp variations - Gonzalez+05 & Huang+17
- Suggests ICL is dynamically young and separate from BCG

ICL fraction in individual clusters varies:
- ~4-21% (in B, Krick & Bernstein 2007)
- ~10-30% (Feldmeier+’04)
- ~5% in Virgo, isolated regions
- ~50% in Bernstein+’95 field in Coma cluster core

Depends on radial range and evolutionary stage of the cluster, large scatter at large radii in HSC survey (Huang+17)
ICL properties in individual clusters

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ICL optical color: it varies, some red, some blue. Recent phot. in nearby clusters show strong blueward gradient (Mihos+17, Huang+17)

Infrared emission: identical to the normal stellar population (ICL is not comprised of brown dwarfs)

Bright galaxies tend to have more extended halos with mass (Kormendy+09, Huang+13, 17)
Observing ICL is difficult...

Because:
1. The signal is, at best, five magnitudes fainter than the night sky
2. Many systematic effects can swamp the results you wish to obtain

Obstacle: Sky subtraction

The effect of a 0.01% error in sky subtraction at faint magnitudes (Gonzalez et al. 2000)

The exact method of sky subtraction (adopting a constant, fitting a plane, or adopting a higher-order function) differs between research groups.
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Obstacle: Flat fielding

Flat-fielding to a precision of 0.1% is critical. Dark-sky flats with little scattered light or drift scanning observations
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Obstacles – Determining the large-scale PSF, and reducing scattered light

The PSF of any object goes out a great distance. At large radii, the profile is caused by dust and imperfections in the telescope. Scattered light from bright stars must be removed from the images, masked (or both).


In this example, by Krick & Bernstein (2007), the PSF has a complex structure. By careful baffling, the scattered light profile can be significantly reduced.
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Obstacle: Separating the ICL from the BCG/cD/Other Galaxies

Uson+1991’s approach: ...``Whether this diffuse light is called the cD envelope or diffuse intergalactic light is a matter of semantics; it is a diffuse component which is distributed with elliptical symmetry about the center of the cluster potential.”...

Or work harder.....

Example data from Seigar et al. (2007)
Dressler 1979, ApJ, 231, 659: ....Spectra of the envelope of the cD galaxy in the rich cluster of galaxies Abell 2029 out to over 100 kpc are analyzed by using a Fourier cross-correlation technique. It is found that the measured velocity dispersion apparently increases with radius, implying that the M/L ratio of the envelope is increasing rapidly.

NGC 6616: single Sersic. ICL clearly signaled by $\sigma$ increase Kelson+01, Bender+15
Disentangle cD from ICL in clusters - use the velocity distribution of stars to classify then according to their binding energy (Dolag+10, Cui+14).

Simulations of clusters - VD is bimodal. Fit by two Maxwellians distribution, one narrower (colder) for the central galaxy and a broader one (hotter) for the ICL.

Hotter component is responsible for the “light excess” at large radii.

Stellar particles in hydrodynamical cosmological simulations thus selected turn out to have different spatial distribution & star formation history.

See also Kapferer et al., 2010, MNRAS, 516, 41.

**Kinematics measurement can tag galaxy and ICL stars from their LOSVD at the same spatial location!**
Examples:
M87 and ICL in Virgo core
M49 and IGL in Virgo subcluster B
Coma
.... But also NGC 1399 in Fornax and
NGC 3311 in Hydra....
And this is where it all started: 3 PNs at $v_{\text{mean}} \sim 1400 \text{ kms}^{-1}$ along the LOS to NGC 4406 ($v_{\text{sys}} = -240 \text{ kms}^{-1}$)  


**Different kinematic components in the Virgo core**

Spectroscopic follow-up with FLAMES@UT2 on VLT; 288 spectr. confirmed PNs. Additional 12 PNs from D09

Using their \( v_{\text{los}} \) PNs can be classified as M87 halo or intracluster!

**Red Gaussian**: M87 halo; 225 PNs

**Blue Gaussian**: ICL in Virgo core; 73 ICPNs

\[
\begin{align*}
\text{M87 Halo} & \quad v_{\text{sys}} = 1275 \text{ km/s} \\
& \quad \sigma_n \approx 300 \text{ km/s}
\end{align*}
\]

\[
\begin{align*}
\text{ICL} & \quad v_{\text{ave}} = 995 \text{ km/s} \\
& \quad \sigma_b \approx 900 \text{ km/s}
\end{align*}
\]

**Line of sight velocity distribution of 300 PNs**


M. Arnaboldi – Observations of the ICL

MPIA, July 2 2018
Halo PNs and ICPNs have different spatial distributions: halo PNs have a steeper radial gradient; ICPNs $\propto R^\gamma$ with $\gamma = [-0.79 \pm 0.15]$.
Different populations in the Virgo core

HST/ACS data for IC field in Virgo, half way between M87 and M86; 36 orbits.

Less than 20% of the stars in the VIRGO IC field have ages < 10 Gyrs

More than 80% of the stars have ages > 10 Gyrs

Most of the stars with e ages > 10 Gyrs have [M/H] < -1.0

Different kin. & spatial components in the Virgo sub. Cluster B – M49

NGC 4472 (M49)
BCG at the center of Virgo subcluster B

495 PNs with LOSVs from Hartke+2018arXiv180503092 & Pulsoni+2017arXiv171205833
Poster by J. Hartke and talk by C. Pulsoni this conference

M. Arnaboldi – Observations of the ICL

MPIA, July 2 2018
Different kin. & spatial components in the Virgo sub.

Cluster B - M49

- Bin-free double-Gaussian model
  - Halo: $\sigma = 170$ km/s
  - IGL: $\sigma = 400$ km/s

Pulsoni+2017arXiv171205833
Hartke+2018arXiv180503092
Different kin. & spatial components in Coma core

- 37 PNs detected
- Their LOSVD is not a single Gaussian
- Multi peaked – secondary bluer peak associated with nearby substructure G7
- Main peak of the PN LOSVD is at 6450 km/s
- Coma core is not virialized

NGC 4874 $\sigma_0 = 300$ km/s
NGC 4889 $\sigma_0 = 400$ km/s
We measure the $v_{\text{LOS}}$ of stars in the diffuse stellar halo in a region near to NGC 4874, but stars’ $v_{\text{LOS}}$ histogram is peaked at $-700\,\text{km/s}$ from its systemic velocity - *Halo velocities are flipped!* 

Gerhard+2005,2007; Arnaboldi+2007

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Gerhard+2005,2007; Arnaboldi+2007
6. Conclusions

• Diffuse light in cluster cores ubiquitous – deep photometry and kinematics from PNs show it is made up of genuine ICL and extended, luminous halos of BCGs. On average, ICL contains ~10% of cluster stellar light, BCG halos further ~10%; substantial variations depending on cluster evolutionary state.

• Kinematics from PNs show that ICL is un-relaxed with discrete velocity components (Virgo, Coma, Hydra) over cluster \( \sigma \) scale. BCG halos are colder; constant (NGC 4889), decreasing (M87, NGC 1399), or increasing (Hydra, collapsed ICL) \( \sigma \)’s. Together with morphology: dynamically distinct components.

• Formation of ICL and outer halos, how and when? Evidence for BCG mergers (Coma+) and tidal disruption/accretion (M87, M49, Hydra) in cluster cores – build-up of BCG halos and nearby ICL continues. Formation of ICL and outer halos on-going and long-lasting process.

• Stellar population characteristics of the halos and the ICL? – Current results for Virgo show they are distinct. More work needed: with ELT Coma will become our backyard & lots to learn!