The intracluster light: the missing piece in the galaxy cluster evolution puzzle

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The hidden Universe
The hidden Universe
The low surface brightness Universe

B $\mu_N$ (mag/arcsec$^2$)

38.0 35.5 33.0 30.5 28.0 25.5 23.0

Bullock & Johnston 2005
The low surface brightness Universe

**PAndAS survey**

\[
\begin{align*}
[\text{Fe/H}] &\sim -2.3 \\
[\text{Fe/H}] &\sim -1.4 \\
[\text{Fe/H}] &\sim -0.7
\end{align*}
\]

\[R_{M33} \sim 50 \text{ kpc}\]

\[R_{M31} \sim 150 \text{ kpc}\]
The low surface brightness Universe
The low surface brightness Universe

- Buildup of structure
  - ICL MM & Trujillo 2014, 2018

- Missing baryons?
  - ICL Gonzalez et al. 2007, 2013

- Missing satellites?
  - LSB satellites? Crjonovic et al. 2016, Bennet et al. 2017

- Dark Matter?
  - Ultra diffuse galaxies van Dokkum et al. 2015, Román & Trujillo 2017a,b

- Other phenomena, e.g.:
  - Astrospheres of dying stars Sahai & Mack-Crane 2014
Observing LSB
Observing LSB
Scattered light

Karabal et al. 2017

Uson, Boughn & Kuhn 1991

Trujillo & Fliri 2016
PSF effect

Mimic stellar halo

Affects more smaller systems

Trujillo & Fliri 2016
Galactic Cirri

Duc et al. 2015

Mihos et al. 2017
Sky subtraction

Aihara et al. 2018

Borlaff et al. 2019
The ICL
The ICL
Diffuse light proposed by Zwicky 1937

field nebulae. In the second place, we should expect a considerable number of stars, as well as matter in dispersed form from disrupted nebulae, to be scattered through the internebular spaces within clusters. Sufficiently large amounts of internebular matter in clusters

and first observed by Zwicky 1951 in Coma

One of the most interesting discoveries made in the course of this investigation is the observation of an extended mass of luminous intergalactic matter of very low surface brightness. The objects which constitute this matter must be considered as the faintest individual members of the cluster. They indicate that the

Image credit: Javier Román

also Zwicky 1957, 1959
The beginning

Trying to solve the “missing” mass problem in clusters of galaxies (Zwicky 1933) De Vaucouleurs 1960; Arp & Bertola 1969; de Vaucouleurs & de Vaucouleurs 1970; Welch & Sastry 1971; Melnick et al. 1977

ICL is 1% of the night sky or fainter!

Thuan & Kormendy 1977

Bluer than the galaxies!

De Vaucouleurs 1960; Arp & Bertola 1969; de Vaucouleurs & de Vaucouleurs 1970; Welch & Sastry 1971; Melnick et al. 1977

Abell 2670 (Oemler 1973)
Today

Deeper and farther

Low-z ($z \sim 0$)
Iodice et al. 2017

Intermediate-z ($z \sim 0.4$)
MM & Trujillo 2019

$z \sim 1.24$
Ko & Jee 2018

What exactly is the ICL?

Distinct stellar component !!!
What exactly is the ICL?

Abell 2029

Dressler 1979

Mihos et al. 2005

σ (km/s)

R (kpc)

Longobardi et al. 2018
Why study the ICL?

Rudick, Mihos, McBride 2006

Encodes merger histories of cluster of galaxies
Why study the ICL?

Rudick, Milos, McBride 2006

Encodes merger histories of cluster of galaxies
Why study the ICL? Buildup of the BCG

Why study the ICL? Buildup of the BCG


If formation of ICL

De Lucia & Blaizot 2007

Contini et al. 2018
Why study the ICL? Buildup of the BCG


If formation of ICL

De Lucia & Blaizot 2007

Contini et al. 2018

Conroy et al. 2007
Origin

e.g. Conroy et al. 2007
Murante et al. 2007

e.g. Rudick et al. 2009
Contini et al. 2014, 2019

e.g. Purcell et al. 2007

Puchwein et al. 2010

e.g. Mihos 2004
Rudick et al. 2006

Puchwein et al. 2010
Stellar properties

Gradients in color and metallicity

Also see Iodice et al. 2017, Mihos et al. 2017 for nearby clusters
Stellar properties

Gradients in color and metallicity

Also MM & Trujillo 2014

MACS1149

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Stellar properties

Gradients in color and metallicity

Also see Iodice et al. 2017, Mihos et al. 2017 for nearby clusters
Stellar properties

Gradients in color and metallicity

DeMaio et al. 2018

MM & Trujillo 2018

Krick & Bernstein 2007

MM & Trujillo 2018

Also see Iodice et al. 2017, Mihos et al. 2017 for nearby clusters

Also MM & Trujillo 2014

20-30%, t<10Gyr, [M/H]>-0.5
70-80% t>10 Gyr, [M/H]~-1.3
(Williams et al. 2007)
Tracer of the dark matter halo

Alonso-Asensio et al. 2020

MM & Trujillo 2019
Tracer of the dark matter halo

A2744

Alonso-Asensio et al. 2020

AS1063

MM & Trujillo 2019
Tracer of the DM halo

Boehm et al. 2014
Tracer of the DM halo

Discern the nature of dark matter?

SIDM

SIDM'

CDM

WDM

AS1063

MM & Trujillo 2019

Boehm et al. 2014
Unveiling the ICL
Unveiling the ICL
Hyper Suprime-Cam

1.5 deg diameter
Abell 85

\[ R_{\text{vir}} = 2.42 \, \text{Mpc} \]
\[ = 0.63^\circ \]

Owers et al. 2017
“Homemade” data reduction

🌟 CCD processing (Bias/ Darks)
“Homemade” data reduction

- CCD processing (Bias/ Darks)
- Flat-field correction
“Homemade” data reduction

- CCD processing (Bias/ Darks)
- Flat-field correction

\[
\langle \text{INR-STR} \rangle = -5 \quad \langle \text{INR-STR} \rangle = 114
\]

Images: \( \langle \text{INR-STR} \rangle = 124 \)

Gradient of 1% across the CCD
“Homemade” data reduction

Abell 85: MM, Brough, Owers & Santucci, 2020, submitted
“Homemade” data reduction

- CCD processing (Bias/ Darks)
- Flat-field correction
- Frame assembly
- Sky subtraction Plane + constant
“Homemade” data reduction

- CCD processing (Bias/ Darks)
- Flat-field correction
- Frame assembly
- Sky subtraction
- Final co-addition

- Star subtraction and masking
Star subtraction

2-D PSF models
Star subtraction & masking

Original

Star subtracted

Masked

i-band
$g_{\text{lim}} = 30.8 \text{ mag/arcsec}^2 (10'' \times 10'', 3\sigma)$

$i_{\text{lim}} = 29.6 \text{ mag/arcsec}^2$
HSC
SDSS
9 x 200 s = 30 min
53.9 s
g-band
Stellar populations of Abell 85

**Diagram:**

- **Sérsic fit**
- **μ₀ (mag/arcsec²)** vs **SMA (arcsec)**
  - **μ₀** (teal) and **Fit g** (green dashed)
  - **μ₁** (purple) and **Fit I** (blue dashed)

- **Ellipticity** and **PA** vs **SMA (kpc)**
  - **Ellipticity**
  - **PA**

**Labels:**
- **g-band**
- **i-band**
Galsies

\[(g - i)_{0}\]

SMA (arcsec)

SMA (kpc)

1.10
1.15
1.20
1.25
1.30
1.35
1.40
1.45
1.50
1
10
100

PSF

\(g - i \sim 1.23\)

\(M^* \sim 10^{10} M_\odot\)

And only in 30 mins!!

Also

MM & Trujillo 2014, 2018
Conclusions

- ICL is **ubiquitous** in clusters of galaxies. Formed by stars following the potential of the cluster.

- The ICL encodes the history of hierarchical assembly of the cluster. And makes simulations agree with the observed BCG mass evolution.

- Luminous tracer of dark matter.

- It forms via tidal stripping of massive satellites.
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- It forms via tidal stripping of massive satellites.
LSB observers be like...