Outer Halos of Cluster Early-Type Galaxies: Growth over Time

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Elliptical Galaxies: an Advanced Stage in Galaxy Formation
- The most massive galaxies
- In dense environments
- Contain the oldest stellar populations

Elliptical Galaxy Halos: Origin and Relation to Environment
- How do they blend into the environment, the Intracluster Light?
- Density of Dark Matter Halos?
- Orbit distribution and dynamics, angular momentum of the halo stars?
- Stellar Populations, Age, Metallicity?
- How did the halos form and what do they tell us about the origin of ellipticals and their evolution in clusters & groups?

Some recent results: stellar densities, dark matter distribution, stellar populations, kinematics, dynamics

Core of the nearby Virgo cluster with luminous galaxies M87, M86, M84 and others

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II. Stellar Densities at Faint SB
Core Ellipticals Have the Most Extended Stellar Halos

Brighter ‘core’ ellipticals have more extended brightness profiles (larger Sersic $n$, larger $R_e$, fainter $\mu_e$), but are brighter at all radii outside their cores than ‘cuspy’ ellipticals.

Within each group, $n$ not correlated with $M_v$.

Kormendy et al. (2009), Virgo sample
Size Evolution of Bright Ellipticals from $z=2$ to now

Recent evidence that $z=1$ and $z=2$ bright ellipticals were smaller and more compact than ellipticals of similar mass today: Daddi+'05, Trujillo+'07, van Dokkum+'08, van der Wel+'09, van Dokkum+'10 construct samples at constant environment number density to show that profiles of stacked images become more extended (larger $n$, $R_e$) with decreasing redshift. Interpretation: accretion of halos through minor mergers Abadi+'06, Naab+'09.
III. Kinematics at Faint SB
Stellar-kinematic Data in the Outer Halos of Elliptical Galaxies

Traditional long-slit kinematics reaches ~2 Re down to surface brightness of $\mu_\text{V} \sim 23.5$

To determine dark matter and halo orbit distribution, need alternative ways to obtain data at larger radii and fainter surface brightness:

- Planetary nebulae, Hui et al. 1995, trace stellar light and kinematics to typically ~8 Re, Coccato et al. 2009, up to beyond 100 kpc, Doherty et al. 2009 (to $\mu_\text{V} \sim 27.5$)
- Slitlets placed around halo globular clusters, Proctor et al. 2009 (to $\mu_\text{V} \sim 25$)
- IFUs placed at large radii, Sauron, Weijmans et al. 2009, VIRUS-P, Gebhardt et al. 2009 (to $\mu_\text{V} \sim 25.5$)
- Globular clusters (not direct light tracers; e.g. Schuberth et al. 2009)

Core of the nearby Virgo cluster with luminous galaxies M87, M86, M84 and others
Outer Halo Kinematics from PNe

- 2 types of slowly falling and rapidly falling kinematic profiles
- Slow/fast rotator division more complicated in the outer halos

Kinematic Misalignments More Frequent at Large Radii

From slitlets:

From PNe:
Extreme outer halo of Virgo-central galaxy M87

- PN velocities obtained down to $\mu_V = 27.5$
- PN with M87 $v_{sys}$ seen only for $R<160$ kpc. At larger radii see ICL with M86 and other v’s. Truncation significant at $\sim 2\sigma$ level (comparing light with PNe, using $\alpha$ value from spectroscopically confirmed PNe), but small numbers.
- Velocity dispersion falls to $78 \pm 25$ km/s at $R_{avg}=140$ kpc and $247 \pm 50$ km/s at $R_{avg}=50$ kpc. Jeans models in the X-ray potential (Nulsen & Boehringer 1995) can reproduce these low $\sigma$ only if the stellar halo is truncated at $\sim 150$ kpc.

Doherty, Arnaboldi, Das, Gerhard et al., A&A 502, 771
The dynamically hot stellar halo around NGC 3311: a cluster dominated small galaxy

- Central galaxy velocity dispersion $\sim 150$ km/s
- In 15”–45” (4-12 kpc) transition to $\sigma \sim 450$ km/s $\sim 60\%$ of dispersion of cluster galaxies
- Outer halo unusually dynamically hot for ETGs
- Intracluster stellar halo dominates completely for R>12 kpc

Ventimiglia et al. submitted
IV. Halo Stellar Populations as Constraints on Assembly History
Stellar Population in the Halo of NGC 4889

Line strength indices Hb, [MgFe]', Mgb, <Fe> measured with deep Subaru spectra to 65 kpc radius.

Fitting Single Stellar Population Models (Thomas et al. 2003) to indices gives for:

\( R \sim 1.2R_e \):
- steep metallicity gradient (from \(~5\) solar to \(~\)solar);
- constant abundance ratio (2.5 solar);

\( R > 1.2R_e \):
- hardly any metallicity gradient
- strong \([\alpha /Fe]\) gradient (drops to \(~\)solar)

Stellar ages increase with radius

\( \Delta \) : stellar population from literature data
- : stellar population from our Subaru data
\( \text{yellow} \) : including sky systematic errors
Constraints on Formation History

Inner half of NGC 4889 (R~<Re)

High central [Z/H] and steep gradients of -0.5 are produced in rapid “monolithic” collapses (Chiosi & Carraro ’02; Kobayashi ’04; Pipino+’06, ’08). Then reduced by subsequent dry mergers (White ’80, Kobayashi ’04, di Matteo+’09).

Constant inner $\alpha$/Fe (~2.5 solar) implies rapid star-forming collapse of entire inner half of the galaxy, ~10$^8$yr (Thomas et al formula) $\sim t_{dyn}$ to ~10$^9$yr, perhaps in dissipative multiple merger.

Younger central ages might be due to minor accretion event (e.g., 10% 1 Gyr ago).

Brough+’07 find range of gradients in BCGs.

Halo (R~>Re)

Near-solar $\alpha$/Fe indicates longer SFH, >~1Gyr. Together with near-solar [Z/H] and lack of gradient $\Rightarrow$ most likely origin is accretion of lower-mass galaxies with long SFH. Preventing central late SF would blow out entire halo gas. Note that the halo stars are old (~10 Gyr). Would be consistent with in situ vs accreted stars in simulations of isolated galaxies (Abadi+06).

Coccato et al. 2010 MNRAS 407, L26
V. Dark Matter Halos
Bayesian reconstruction from deprojected temperature and density profiles, assuming hydrostatic pressure equilibrium $\Rightarrow$ circular velocity curves rising, probably due to group halo

Top left: mean/median circular velocity curves with 95% CL for a sample of 6 XRBE’s. Mass profiles have overall mean $\alpha = 1.21$ and outer (>10 kpc) $\alpha = 1.56$ for $M \propto r^\alpha$.

Middle top: dark matter mass fractions $\sim 60$-80% at 20-30 kpc

Right: Galaxy luminosity and circular velocity at Re correlate with velocity dispersion of environment on sub-Mpc scale.

Supports embedding in group-size halo and link between central XRBEs and their environment.

Dark Halo Circular Velocity Curves from Stellar Kinematics

Approximately flat for luminous round galaxies, using data to 1-2 Re, non-parametric spherical DF models Gerhard et al. (2001). Panels roughly in order of decreasing luminosity.

Extended PNe velocity dispersion profile steeply falling

Steeply falling dispersion profile in NGC 3379 is consistent with little dark matter if the galaxy is isotropic Romanowsky+03 Douglas+07
Halo Dynamics in NGC 3379 & NGC 4697

Best axisymmetric models for NGC 3379 (red) and NGC 4697 (blue) have moderately falling circular velocity curves and radially anisotropic halos (de Lorenzi et al. 2008, 2009). Shaded range is for models from Dekel et al. 2005, including $v_{\text{rot}}$ in $\beta$ values.

Strongly falling dispersion profiles in NGC 3379, NGC 4697 do not necessarily imply non-standard diffuse halos, but may be consistent with predicted scatter.

Overall results indicate range of mass profile slopes in ellipticals.
Sample of 17 early-type galaxies in the Coma cluster, kinematic data to ~ 2-3 Re, Schwarzschild orbit superposition models in luminous + halo potentials

- Dark matter densities 7x higher than in spirals of same L (13x higher at same M), less luminous Es have higher halo densities
- Baryonic contraction not sufficient to explain the difference
- Elliptical galaxies assembled earlier than spirals of same luminosity

Thomas et al. 2009

Coma early-types
Round galaxies (Gerhard et al. 2001)
Spirals (Kormendy & Freeman 2004)
Spirals (Persic, Salucci & Stel 1996)
VI. Dynamics
Best axisymmetric models for NGC 3379 (red) and N4697 (blue) have moderately falling circular velocity curves and radially anisotropic halos (de Lorenzi et al. 2008, 2009). Shaded range is for models from Dekel et al. 2005, including $v_{\text{rot}}$ in $\beta$ values.

Strongly radially falling dispersion profiles in NGC 3379, NGC 4697 do not necessarily imply non-standard diffuse halos, but may be consistent with predicted scatter.
Extended Anisotropic Halos in Simulations

- Isolated elliptical galaxies in simulations (Abadi et al. 2006) acquire extended, radially anisotropic halos built from accretion of smaller galaxies. See also Naab et al. 2009.
- Level of predicted anisotropy consistent with results from some nearby ellipticals studied so far.
VII. Summary and Conclusions (1)

- Extended, low surface brightness halos in bright elliptical galaxies (M87: \( \sim 150 \text{ kpc} \)). Kinematics can be measured with PN (to \( \mu_v = 27.5 \), up to \( 8 \text{ Re} \) but low numbers) and slitlets/IFU based techniques (up to 3-4 Re, \( \mu_v = 25 \)) or slits (\( \mu_v < 24 \)).

- Halo kinematics:
  - The basic slow/fast rotator dichotomy of elliptical galaxies also holds in the halos but halo \( \lambda \) -profiles more diverse. Dispersion profiles either slightly, or strongly falling. Kinematic misalignments (and triaxiality?) more frequent in the halos.
  - Reach the transition between galaxy and intracluster light in M87 and NGC 3311:
    **outer halo of M87 truncated and anisotropic; beyond 150 kpc encroaching stars of M86 and other galaxies, probably prior to substantial dry merger**
    **outer halo of NGC 3311 in Hydra is the central intracluster light component**

- Halo stellar population of Coma BCG NGC 4889:
  - Distinct populations inside 1.2 Re and in the halo.
  - Steep inner metallicity gradient and 2.5 solar \([\alpha/Fe]\) imply rapid formation, possibly rapid dissipative merger “quasi-monolithic” collapse followed by 1-2 dry mergers.
  - Solar metallicity and more nearly solar \([\alpha/Fe]\) imply longer star formation history for halo stars, accreted later onto preexisting inner galaxy.
  - May be local signature of size evolution observed for high-z ellipticals.
V. Summary and Conclusions (2)

• Dark matter halos in elliptical galaxies:
  – New non-parametric Bayesian analysis of X-ray data imply high-density halos with rising \( v_c \) in XRBES, \( \sim 60-80\% \) within 20-30 kpc in XRBES. X-ray – optical comparison: Non-thermal central pressure in X-ray bright E’s at \( \sim 20-30\% \) level.
  – Strongly radially falling dispersion profiles in NGC 3379, NGC 4697: probably halos on the low density side of the predicted scatter in LCDM. Based on new made-to-measure adaptive particle method NMAGIC.
  – On average, circular velocity curves to \( \sim 2 \) \( R_e \) approximately flat (dynamics and strong lensing; high L!??) but there are variations, \( \sim 10-40\% \) DM within \( R_e \).
  – Central dark matter density in ellipticals \( \sim 7 (\sim 13) \) times higher than in spirals of same L (baryonic mass); core assembly redshift \( (1+z) \) \( \sim \)twice higher, i.e. \( z=1…3 \).

• Halo orbital structure:
  – Some outer halos of ellipticals are radially anisotropic, consistent with \( \Lambda \) CDM simulation results – more work in progress.

• Future:
  – Towards representative samples: More and better kinematic and stellar population data
  – Combine different tracers in improved dynamical models