Dynamic modelling of luminous and dark matter in 17 Coma early-type galaxies


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A Little Background

• Elliptical Galaxies
  – Numerous among bright galaxies
  – Harbor significant fraction of stellar mass in the Universe

• Key Parameters for Elliptical Galaxy Formation
  – Central dark matter density
  – Scaling radius of dark matter
  – Stellar mass-to-light ratio
  – Distribution of stellar orbits
Purpose of Dynamic Modelling

- Allows for reconstruction of mass structure and orbital state of galaxy
  - Requires high quality Line-of-Sight Velocity Distributions (LOSVDs) out to several Reff (1/2 light radius)
- What has been done:
  - Only large non-rotating Ellipticals have been probed with spherical models.
  - Authors will look at nonsymmetrical, rotating and nonrotating models.
    - Looking for evidence of dark matter
- Goal: Analyze the luminous and dark matter distributions and orbital structure of flattened Coma galaxies
Observations

• Coma Sample: 17 early-type galaxies
  – 2 cD, 9 ordinary giant elliptical, and 6 lenticular galaxies
    • -20.30 < Mb < -22.56
    • H0 = 69 km/(s*Mpc)
    • 3.3 < reff < 18.4 (arcsec)

• Data obtained from HST (inner parts) and ground based (outer parts)
  – Data obtained along 2 position angles
    • Apparent Major and Minor Axes.
Table 1. Summary of observational data. Columns (1) and (2): galaxy ID (GMP from Godwin, Metcalfe & Peach 1983); column (3): morphological type (from Mehlert et al. 2000); columns (4) and (5): HST and ground-based photometry (L97 = HST/WFPC2 R-band data, Principal Investigator: John Lucey, Proposal ID: 5997; H98 = HST/WFPC2 R-band data, Principal Investigator: William Harris, Proposal ID: 6104; W07 = HST/WFPC2 R-band data, Principal Investigator: Gary Wegner, Proposal ID: 10884; M00 = Kron–Cousins Rc-band photometry from Mehlert et al. 2000; J94 = Gunn r photometry from Jørgensen & Franx 1994); column (6): absolute B-band magnitude (from Hyperleda; \( \text{H}_0 = 69 \text{ km s}^{-1} \text{ Mpc}^{-1} \)); columns (7) and (8): effective radius \( r_{\text{eff}} \) and ellipticity \( \epsilon_e \) at \( r_{\text{eff}} \) from Mehlert et al. (2000); column (9): rms \( (\mu_{\text{grd}} - \mu_{\text{HST}}) \) between shifted HST surface brightness \( \mu_{\text{HST}} \) and corresponding ground-based \( \mu_{\text{grd}} \); columns (10)–(13): radius of the outermost kinematic data point along various slit positions: maj/min/dia = position angle of \( 0^\circ/90^\circ/45^\circ \) relative to major axis; off = parallel to major axis (in case of GMP5568: two offset-slits). The offsets are quoted in the captions of Figs A1–A17.

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Deprojection and inclination

- Surface photometry is deprojected to form 3D luminosity function ($\nu$)
- Inclinations
  - 3 different inclinations are used
    - $I = 90^\circ$ (edge on)
    - A minimum inclination that is found by requiring the deprojection to be as flattened as an E7
    - Intermediate inclination for which the deprojection looks like an E5
  - In many galaxies, inclination is poorly constrained
NGC 4624. E7 in Virgo

NGC 4621. E5 in Virgo
Mass Model

\[ \rho = \gamma v + \rho_{\text{DM}} \]

- Trial mass density, combination of stellar mass to light ratio and dark matter density.

- Two different density functions are used to fit the kinematic data. NFW distribution and a LOG distribution.

\[
\rho_{\text{NFW}}(r, r_s, c) \propto \frac{1}{(r/r_s)(1 + r/r_s)^2} \\
 r_s^3 \propto 10^{(A-\log c)/B} \left( \frac{4\pi}{3} \frac{c^3}{200} \right)^{-1} \\
r \rightarrow r \sqrt{\cos^2(\vartheta) + \sin^2(\vartheta)/q^2} \\
A = 1.05 \text{ and } B = 0.15
\]

\[
\rho_{\text{LOG}}(r) \propto v_c^2 \frac{3r_c^2 + r^2}{(r_c^2 + r^2)^2}
\]
Orbital Superposition

\[ \dot{S} \equiv S - \alpha \chi^2_{\text{LOSVD}} \rightarrow \max \]

\[ f_i \equiv \frac{w_i}{V_i} \]

\[ S \equiv -\int f \ln(f) \, d^3r \, d^3v = -\sum_i w_i \ln \left( \frac{w_i}{V_i} \right) \]

\[ \chi^2_{\text{LOSVD}} = \sum_{j=1}^{N_L} \sum_{k=1}^{N_{vel}} \left( \frac{L_{j,k}^{\text{mod}} - L_{j,k}^{\text{dat}}}{\Delta L_{j,k}^{\text{dat}}} \right)^2 \]

\[ \beta_\theta \equiv 1 - \frac{\sigma_\theta^2}{\sigma_r^2} \]

\[ \beta_\varphi \equiv 1 - \frac{\sigma_\varphi^2}{\sigma_r^2} \]

- \( S \) -> Boltzmann entropy
- \( f \) -> phase-space distribution function
- \( W_i \) -> total amount of light on the orbit
- \( V_i \) -> orbital phase-space volume
- \( \alpha \) -> regularization
- \( \chi^2_{\text{LOSVD}} \) -> deviations between data and mode
- Betas -> Anisotropy
What is this $\alpha$?

- Controls the relative weight of data fit and entropy maximization.
- The higher $\alpha$ the better the fit, but noisier the DF becomes.
- $\alpha = 0.02$ for all modelling
Goodness-of-fit

\[ \chi^2_{GH} \equiv \sum_{j=1}^{N_C} \left[ \left( \frac{v^j_{\text{mod}} - v^j_{\text{dat}}}{\Delta v^j_{\text{dat}}} \right)^2 + \left( \frac{\sigma^j_{\text{mod}} - \sigma^j_{\text{dat}}}{\Delta \sigma^j_{\text{dat}}} \right)^2 \right. \\
\left. + \left( \frac{H^j_{3,\text{mod}} - H^j_{3,\text{dat}}}{\Delta H^j_{3,\text{dat}}} \right)^2 + \left( \frac{H^j_{4,\text{mod}} - H^j_{4,\text{dat}}}{\Delta H^j_{4,\text{dat}}} \right)^2 \right] \]

- Best fit is determined by above eqn

\[ \chi^2_{\text{SC}} = \min \left\{ \chi^2_{GH}(\nu, \gamma, i)/N_{\text{data}} \right\}, \]
\[ \chi^2_{\text{LOG}} = \min \left\{ \chi^2_{GH}(r_c, \nu_c, \gamma, i)/N_{\text{data}} \right\}, \]
and
\[ \chi^2_{\text{NFW}} = \min \left\{ \chi^2_{GH}(c, q, \gamma, i)/N_{\text{data}} \right\} \]
\[ \chi^2_{\min} = \min \left\{ \chi^2_{\text{LOG}}, \chi^2_{\text{NFW}}, \chi^2_{\text{SC}} \right\} \]

- Most fits are better than \( \chi^2_{\min} < 0.1 \)
Table 2. Summary of modelling results. Column (1): galaxy id (cf. Table 1); columns (2) and (3): best-fitting stellar $Y_{SC} [M/L]\ (R_{C}-band)$ and achieved goodness-of-fit $\chi_{SC}^2$ (per data point) without dark matter; columns (4)–(7): the same as columns (2) and (3), but for LOG haloes with parameters $r_c$ (kpc) and $v_c$ (km s$^{-1}$); columns (8)–(11): the same as columns (2) and (3), but for NFW haloes with concentration $c$ and flattening $q$; columns (12) and (13): best-fitting halo profile with significance $\Delta \chi^2_{halo} = (\chi^2_{NFW} - \chi^2_{LOG}) \times N_{data}$; column (14): evidence for dark matter $\Delta \chi^2_{DM} = (\chi^2_{SC} - \chi^2_{min}) \times N_{data}$; column (15): inclination of best fit with minimum and maximum in the 68 per cent confidence region of calculated models (where no range is quoted, only edge-on models were calculated).

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Model Inclinations

• Most of the best fits are edge on
  – Does this mean there is a bias in model?
• Possible biases
  – Using the same $\alpha$ for all galaxies
  – For face on galaxies, noise in kinematics
  – Non random inclinations
  – Bias due to extreme cases
Model Inclinations 2

- Top: Axial ratio from data (apparently)
- Bottom: Axial ratio from models
- If biased, we would see most galaxies at 1.

*Figure 3.* Top panel: histogram of apparent short-to-long axial ratios at $r_{\text{eff}}$. Bottom panel: intrinsic best-fitting short-to-long axial ratio $b/a$ (averaged over $r/r_{\text{eff}} \in [0.5, 2.5]$). Black/solid line: whole sample; red/dashed line: without S0s.
Luminous and Dark Matter

• Does mass follow light?
  – Best fitting models include a dark matter halo.

• All galaxies fall into 3 categories
  – Inconsistent with a constant mass to light ratio (8/17)
  – Models with and without dark matter differ but, evidence for DM is less than $2\sigma$ (5/17)
  – Evidence for DM is generally weak (4/17)
Circular velocity curves
• Polar region
  – $\beta_v = \beta_\varphi$ due to axial symmetry
  – Center is not constrained
  – Galaxies differ in amount of anisotropy
Velocity Anisotropy

- Equatorial Plane
  - Meridional
    - All have $\beta_\nu > 0$ over sampled range.
    - Average $\beta_\nu$ is related to flattening of galaxy
    - Poorly constrained
  - Azimuthal
    - Much more diverse than Meridional
Phase-Space Distribution
Function of the Stars

• Stationary systems
  – DF is function of the isolating integrals
  – Constant along an orbit
    • Look at: Energy, Lz, 3rd integral, be positive
    – Since the Schwarzschild model exists, it ensures that the luminous component of the model is stationary and physically meaningful

\[ \langle r_{\text{orb}} \rangle_i \equiv \sum \frac{\Delta t_i^k}{T_i} r_i^k, \]
Phase Space Distribution Function of Dark Matter

- Without baryons, DF’s for halo profiles are known. But with baryons it is not so.
- To find DM DF, solve: \[ \hat{S} = S - \alpha \chi_{\text{LOSVD}}^2 \rightarrow \text{max} \]
- But, with alpha = 0
- Use dark matter profile as boundary condition
- Turns out that there does exist a DF for the DM.
LOG vs NFW

• 13 of 17 best fit haloes are LOG
• Significance of fit between profiles is low. No clear distinction can be made.
• With kinematic data, one or the other halo type cannot be rules out.
• Shape and structure of LOG halo DFs do make them unlikely
• Dark Matter phase space densities
Regularization

- $\alpha = 0.02$ was chosen for all Coma Galaxies.
Influence on Model Kinematics

- Minor Axis
  - Max entropy fits ($\alpha$->0) yield isotropy
  - Lowering the weights (w) increases anisotropy
- Major Axis
  - No trend as seen in minor axis
  - Variations in intrinsic velocity anisotropies with alpha are weaker than along minor axis
- Bottom Line: No clear trend of velocity anisotropies with $\alpha$ is notable
Summary I

• 17 Coma Early-type galaxies surveyed
  – Axisymmetric Schwarzschild models used to fit LOSVDs out to 1-4 Reff.
  – 2 Different profiles used
  – Models regularized towards maximum entropy
Summary II

- Models with dark matter fit better than those without.
- NFW haloes fit 4/17 best
- LOG haloes fit 13/17 best
- Central Dark matter densities are at least 1-2 orders of magnitude lower than mass densities
- Between 10-50 % of mass inside Reff is dark matter
- Circular velocities is fairly constant over observed region
- All dark haloes are supported by at least 1 phase space DF
Summary III

- Rotation comes from overpopulation of prograde orbits and underpopulation of retrograde orbits
- Strong tangential anisotropy along minor axis
- \( \alpha \) does not matter!
Ok. Now I am done.

• Questions? Comments? Rude Remarks?

• Thanks!