Deep imaging - using new instrumentation to decipher the structure of galaxies

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Galaxy morphology

- One of the main tools for understanding galaxies and their formation and evolution is studying their morphology.
- Dates back many years, and sophisticated modern approaches include detailed classification, components, and various degrees of automation.
Faint structures: Truncations, thick disks, haloes, tidal streams, etc...

- Main models of cosmological galaxy formation and evolution postulate important role for interactions and mergers in shaping current-day galaxies
- Direct results of these processes include various forms of structure in the outer parts of galaxies...
- ...as well as a population of very faint dwarf galaxies
- Longer dynamical timescales mean that results of early processes survive longer, and evolution is slower

- But deep imaging is needed and this comes with its problems...
Early deep imaging

Photographic plate by David Malin of M83
Recent advances: CCDs and small telescopes

Merritt et al. 2016

Martínez-Delgado et al. 2010

Miho et al. 2013
Issues with deep imaging (I)

- Sky brightness
- Internal reflections
- Flat fielding
- Masking and background subtraction

Stripe82, NGC 941, Peters et al. 2017
Issues with deep imaging (II)

Scattered light

 Depth: \(\sim 28.5 \text{ mag/arcsec}^2\)
\(3\sigma \ (10'' \times 10'')\)

Galactic Cirrus

See Knapen & Trujillo 2017
Ultra Diffuse Galaxies

\( \mu_g(0) > 24 \text{ mag/arcsec}^2 \)

\( r_e > 1.5 \text{ kpc} \)

Román & Trujillo (2017b)
The IAC Stripe82 Legacy Project
Science case examples
Dust cirrus

Román, Trujillo & Montes (2018; in preparation)
The IAC Stripe82 Legacy Project
Science case examples
Outskirts of galaxies

Román et al (2019, in prep.)
Martínez-Lombilla et al. (2018; in preparation)

UGC01040
The IAC Stripe82 Legacy Project
Science case examples
Galaxy streams

Chamba et al (2019, in preparation)
Edge-on galaxies

• Give unique access to important aspects of disks
• Along major axis: truncations, warps
• Perpendicular: thick disks, haloes

• Will concentrate here on truncations and thick disks
Example: Thick Disks

- Thick disks are seen in edge-on disk galaxies as excess of light typically at a few thin disk scale heights
- Known since late ’70s (Tsikoudi, Burstein)
- Found in our Milky Way
- Nearly ubiquitous (Yoachim+ 2008, Comerón+ 2011a)

Burstein 1979
Origin of thick disks unclear

• **Heating** of originally thin disk, which increases stellar velocity dispersion
• Consequence of **in situ** star formation, with high initial velocity dispersion (thin disk formed later)
• Formed through **interactions** with satellite galaxies, either by dynamical heating of accretion of stars

• Closely related to early evolutionary phases ➔ cosmological importance
• Depending on formation mechanism, also very tightly related to secular evolution

• Thick disks visible thanks to deep mid-IR imaging (now with full PSF correction, Comerón et al. 2018)
Thick disks contain significant mass

Figure: Ratio of thick to thin disk masses (red line is unity = equal mass), as function of disk circular velocity.

Comerón et al. (2011, 2018), using S$^4$G Spitzer IR imaging and PSF correction

Thick disks approx. as massive as thin disks, less so in more massive galaxies

In situ formation most likely, starting at high redshift. For high-mass galaxies secular origin also possible
Thick disks and bulges built early

Figure: Ratio of ‘hot’ to ‘cold’ mass, as function of disk circular velocity (proxy for mass)

Hot: CMC + thick disk;
Cold: thin + gas disks

Ratio hot/cold does not depend on galaxy mass

Roughly half of the mass formed with high dispersion, in phase of high star formation – second half in low SF phase

High SF phase corresponds to early history: high accretion phase
Comerón et al. 2014
Truncated galaxy disks

- Truncations first found in edge-on galaxies (van der Kruit 1979, van der Kruit & Searle 1981)

- Edge-on galaxies grow along minor axis but not radially in deeper exposures

(image from van der Kruit & Freeman 2011 ARAA)
More on truncations

• Commonly found in edge-on galaxies
• Elusive in face-on galaxies – expected at around 27-27.5 r-mag/arcsec²

• Two main families of models for origin of truncations:
  • Suppression of star formation below a certain gas density threshold for local instability
  • Truncation corresponds to maximum in specific angular momentum distribution of present disk, and might correspond to that in protogalaxy
Looking for haloes and truncations: NGC 936 in Stripe82

SDSS Stripe82 covers 270 sq. degrees in equatorial plane, imaged multiple times (up to ~80) in all 5 filters

Shown in Figure: SDSS, IAC-Stripe82. SB levels 26.5, 28.5 mag/arcsec$^2$
Example of a (bright) halo

In NGC 7398 ($\mu=26.1$, $r=16.3$ kpc)

Peters et al. 2017
Example of a truncation

In IC 1516 ($\mu=28.0$, $r=42$ kpc)
Effects of PSF?

• Can faint wings of Point Spread Function add artificial light to ‘halo’?
• Faint stars not enough – brighter stars saturated
• We combine very bright and fainter stars to create ‘super-PSF’ and model our galaxies with it
• Result: indeed substantial contamination
• PSF light not from core, but from disk of galaxy!

(Fliri & Trujillo, 2016)
PSF Test

PSF test for IC 1515

Dots: Observed

Red: Sersic (bulge)
Green: double expon. disk
Magenta: total

Light lines: original
Heavy lines: PSF-convolved

Lower panel: difference

Conclusion: half of total ‘halo’ light due to PSF

Peters et al. 2016
Results from Peters et al. (2017)

• Some truncations detected (typical $\mu=27$)
• Haloes detected in most galaxies (typical $\mu_r=27.5$)
• Disk breaks common (typical $\mu=23$)
• Sizes of all features correlate with galaxy size, and truncations are same size as onset of halo
  • Strange: halo size knows about disk size?
  • OK: truncations integral part of disk?
• Truncations only observed when halo is absent (which may mean fainter than say $\mu=29$)
Truncations in two nearby edge-ons
Truncations:

1. More prominent in UV/blue than in (infra)red
2. Position does not change with wavelength
3. Position does not change with altitude above disk midplane

From Martínez-Lombilla et al. 2019
Truncations in NGC 4565 and 5907

• Results show that truncation is a stable feature of the thin disk

• Lack of change in position with height on disk allows us to place a limit on the growth rate of the disk of 0.5 kpc/Gyr
  • Assuming disk growth while stars reach certain height above plane

Martínez-Lombilla et al. 2019 and PhD thesis
Upcoming: NGC 4565 with the PAUCam @ WHT

- Filter g, r and i
- 4h/filter on source
- Depth: 30 mag/arcsec² (3σ 10”x10”)

Infante-Sáinz et al (2019, in preparation)
Deep GTC imaging of UGC 180

• Work by Ignacio Trujillo & J. Fliri (2016)
• 8 hours $r'$ imaging with 10.4m GTC – possibly deepest image ever
• Seeing 0.9, FOV 8x8’, reach 33 mag/arcsec$^2$ in radial profile (similar depth to star counting techniques in M31 or other nearby galaxies)
• Find that halo mass is 3% of total stellar mass
• Great illustration of what is possible – and of the difficulties encountered
  • PSF
  • Foreground emission
Exquisite PSF to resolve the issue of scattered light (de Jong 2008; Sandin 2014; 2015)

Gamma Draconis
V=2.36 mag
Distribution of scattered light

Original

Scattered light

Scattered light subtracted
Effect of PSF on surface brightness distribution of UGC 00180

Trujillo & Fliri (2016)
Effect of PSF on surface brightness distribution of UGC 00180
Why go beyond 30 mag/arcsec$^2$?

- Characterise stellar haloes
- Find low-mass satellites
- Find ICL at high redshift

Cooper et al. (2010)

Rudick et al. (2006)

Sawala et al. (2016)
What happens to M100 down to 33 mag/arcsec$^2$?

M100 = NGC 4321. Image credit DAGAL, SDSS, S$^4$G, www.dagalnetwork.eu
M100 down to 33 mag/arcsec$^2$

120 kpc (25’) radius

Assumptions:
- nice background,
- continuing exponential profile,
- no stellar PSF problems…

With flatter halo profile: even bigger (200, 300 kpc?)
Conclusions

• The structure and morphology of galaxies yields powerful clues to the formation and evolution

• Deep imaging is subject to several systematic effects but with care they can be handled

• Thick disks contain significant mass, and formed early on

• Truncations are fundamental and stable features of thin disks

• Upcoming surveys such as LSST will deliver science from huge samples – if we deal with systematics and automate the analysis
IAC PhD positions

• Several positions available for applicants world-wide
• Call will be published in a few weeks
• Deadline probably of order April 1st

• If interested, talk to myself or Jesús Falcón-Barroso
Conference webpage:  
http://www.iac.es/congreso/iaus355/

Registration is open.

IAU grants available, apply by March 15th