The stellar mass functions of spheroids and discs

Simon Driver
Univ. Western Australia
Univ of St Andrews

① Large surveys
② Mass fns of ellipticals, bulges, and discs
③ Inclination and dust attenuation
④ Energy output of spheroids and discs
⑤ A simple two-phase model
⑥ Discussion points
Key collaborators/contributors

Joe Liske (ESO)

Alister Graham (Swinburne)

Paul Allen (City)

Lee Kelvin (Innsbruck)

Rebecca Lange (UWA)

Aaron Robotham (UWA)

Mehmet Alpaslan (St Andrews)
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Large Galaxy Surveys: SDSS, MGC, GAMA & WAVES
(with redshifts)

10k redshifts
$uBgrizYJHK$
B<20mag
1” spatial res, 30 sq deg
http://www.eso.org/~jliske/mgc/

250k redshifts
UV-Opt-IR-Radio
r<19.8mag
0.7” spatial res, 250 sq deg
http://www.gama-survey.org/
Driver et al (2011)

2million redshifts
UV-Opt-IR-Radio
r<22mag & phot-z
0.2” spatial res, 1000 sq deg
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Structure on 1kpc to 100Mpc scales

Cosmology:
- Driver & Robotham (2010), cosmic variance
- Blake et al (2013), growth of structure tracers
- Robotham et al (in prep), halo mass function

Filaments, tendrils and voids (1-100Mpc):
- Alpaslan et al (2013), 500 filaments
- Alpaslan et al (2013, submitted), Tendril discovery

Galaxy groups (100kpc-1Mpc):
- Calvi, Poggianti & Vulcani (2011), 176 groups (PM2GC)
- Robotham et al (2011), 14k groups (G³Cv1)
- Robotham et al (in prep), 24k groups (G³Cv2)

Galaxy structure (~1-10kpc):
- Allen et al (2006), 10k GIM2D bulge-disc decomps
- Driver et al (2007), 10k GIM2D, bulge-disc mass densities
- Driver et al (2008), 10k GIM2D, dust attenuation
- Kelvin et al (2011), 150k Sersic profiles
- Kelvin et al (2013a,b), 3k Hubble type Mass Functions
- Kelvin et al (in prep), 3k GALFIT3 decomps
- Lange et al (in prep), z<0.1 bulge-disc mass-size relations
- Lange et al (in prep), 30k GALFIT3 decomps
Energy output of galaxies

20 band photometry
FUV-Opt-NIR-MIR-FIR
HI gas and dynamics via ASKAP

Australian-SKA Pathfinder
Thirty-six 12m antennas with phase array feeds
30 sq deg field of view
GAMA23 region primary deep target
Operations with 12 antennas comence Dec-2014
HI to z=0.45
Galaxy And Mass Assembly (GAMA)

240,000 galaxies to r<19.8mag over four 60 sq deg (~98% complete, selected from SDSS)
- catalogue of 25,000 groups (halos) to $10^{12}M_\odot$
- 20 band photometry + gas (ASKAP) [GALEX+VST+VIKING+WISE+Herschel]
- structure on 1kpc to 100Mpc scales to z~0.2
- DR2 available via http://www.gama-survey.org/dr2/
AAO RESPONSIBLE FOR 35% OF ALL KNOWN REDSHIFTS
60% SDSS
5% Others

UKST
6dF
TAIPAN

AAT
2dFGRS
WiggleZ
MGC
GAMA
OzDes
January 2012 Bushfire: No significant damage to AAT
Operations resumed within 1 month
Observers accommodation destroyed
AAO now operated via Sydney
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GIM2D bulge/disc decompositions

- 96% redshift completeness (AAT/GEMINI) to B=20.0 mag, Driver et al (2005)
- All data available online: http://www.eso.org/~jliske/mgc/
Advantage of MGC

Image quality: B-only, 1” resolution

Surface brightness limit: 26 mag/sq arcsec

Still the best wide area imaging+z dataset about to be superseded by GAMA+VST: ugri, 0.7”, 26 mag/sq arcsec

Driver et al (2005)
The Logical Filter

Allen et al. (2006)
The Logical Filter

Identified 8 characteristic profile shapes:
- Type 1: classic bulge + disc
- Type 2: suppressed bulge
- Type 3: inner & outer bulge
- Type 4: inverted
- Type 5: suppressed disc
- Type 6: inner & outer disc
- Type 7: spheroid only
- Type 8: disc only
Two pop’s or two components?

Sersic only fits

Bridging population

BULGE
DISK

DECOMP’

No bridging population

Exponential discs

Truncated discs

Spheroids

Bulge+disc fits

Sersic only fits

Bridging population

BULGE
DISK

DECOMP’

No bridging population

Exponential discs

Truncated discs

Spheroids
Stellar mass functions (dust corrected)

The Stellar Mass Function (Components)

- Discs
- Bulges
- Ellipticals
- Blue Spheroids

(c2008, unpublished)
The baryon breakdown at z=0

- Dark Energy 72%
- Dark Matter 24%
- Normal Matter 4%
  - Gas 91.7%
  - Stars 8.3% (60% in Discs, 27% in Bulges, 10% in Ellipticals)
  - Dust 0.008%
  - Supermassive Black Holes 0.01%
  - Stars in Blue Spheroids 3%
Mass functions by Hubble type

Selection:
- $0.025 < z < 0.06$ - similar to Gadotti (2009)
- Mass $> 10^{9.5}$ - deeper than Gadotti (2009)
- 3000 systems only
- Will push deeper once VST KiDS data processed

Classification by eye (3 pairs!):

GALFIT3 profiling based on eye classifications

Kelvin et al (2013)
Mass functions by Hubble type

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Kelvin et al (2013)
GALFIT3 Bulge-disc decompositions 3000 galaxies (0.025 < z < 0.06)

Kelvin et al (20143, PhD thesis), see talk on friday
Major discrepancy for Es!

Selection by Sersic index > 2.5

GAMA: Kelvin et al (2013)
Selection by eye
Can we distinguish E’s from S0’s?
Can we distinguish E’s from S0’s?

See Lisa Fogarty’s talk)
e.g., eyeball elliptical: G534655

\[ \text{BIC} = \chi^2 + k \cdot \ln(n) \]
e.g., eyeball elliptical: G534655

\[ \text{BIC} = \chi^2 + k \cdot \ln(n) \]
e.g., eyeball elliptical: G534655

\[ \text{BIC} = \chi^2 + k \cdot \ln(n) \]
e.g., eyeball elliptical: G534655

\[ \text{BIC} = \chi^2 + k \cdot \ln(n) \]
Elliptical, classical bulges and pseudo bulges

Ellipticals,
Classical bulges
Pseudo bulges appear to lie in distinct regions

Need high-S/N

Gadotti (2009)
Consensus on the stellar mass budget

  10% E, 27% bulges, 60% discs, 3% BS

- Gadott (2009):
  25% E, 20% cbulges, 5% pbulges+bars, 50% discs

- Tasca & White (2011):
  50% discs  50% spheroids

- Kelvin (2012, PhD)
  32%E, 14% cbulges, 6.5% pbulges, 48% disc

Let's say 50:50
**Upper limit for bulges!**
**Lower limit for discs!**

Kelvin et al (2013, PhD thesis), see talk on Friday
Discs and bulges form via two (or more) distinct process (dynamically hot v cold).

However mergers will convert both the bulge and disc mass into spheroids.

Some (gas) mass may be returned but stellar mass of disc and bulge both end up in bulge.

Ergo: z=0 spheroid mass is lower limit to stellar mass formed in spheroids.

Dominant process by which stars form is the disc formation process.
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Bulge & disc luminosity functions

Bulge and disc luminosity functions versus inclination, no dust = no change

Driver et al (2007)
Dust attenuation

Dust attenuation severe

Luminosity Function significantly affected by dust attenuation (Driver et al 2008)

Photon escape fraction: 50% of starlight is lost to dust
Dust: Recent (optical) papers

- Shao et al (2007)
- Choi et al (2007)
- Graham & Worthy (2008)
- Balin & Harris (2008)
- Unterborn & Ryden (2008)
- Padilla & Strauss (2008)
- Cho & Park (2009)
- Maller et al (2009)
- Ganda et al (2009)
- Masters et al (2009)
Confirmation via far-IR

Starlight lost = far-IR emission

Little room for any AGN heating

Does this affect the mass estimates?
Significant impact for edge-on systems

Table 1. Schechter function parameters for various galaxy samples with varying degrees of dust attenuation corrections.

<table>
<thead>
<tr>
<th>Component</th>
<th>( M^* - 5 \log h ) (mag)</th>
<th>( 10^8 h M_{\odot} \text{ Mpc}^{-3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discs:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>uncorrected</td>
<td>-</td>
<td>( 3.8 \pm 0.4^d )</td>
</tr>
<tr>
<td>inclination corrected</td>
<td>-</td>
<td>( 4.7(5.0)^c \pm 0.5^d )</td>
</tr>
<tr>
<td>inclination &amp; face-on corrected</td>
<td>-</td>
<td>( 4.1(4.4)^c \pm 0.3^d )</td>
</tr>
<tr>
<td>3.33 \times (1 - \cos(i) &lt; 0.3)</td>
<td>-</td>
<td>( 5.3 \pm 1.2^d )</td>
</tr>
<tr>
<td>3.33 \times (1 - \cos(i) &lt; 0.3) &amp; face-on corrected</td>
<td>-</td>
<td>( 4.7 \pm 0.9^d )</td>
</tr>
<tr>
<td>Bulges:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>uncorrected</td>
<td>-</td>
<td>( 1.6 \pm 0.3^d )</td>
</tr>
<tr>
<td>inclination corrected</td>
<td>-</td>
<td>( 2.3(2.4)^c \pm 0.3^d )</td>
</tr>
<tr>
<td>inclination &amp; face-on corrected</td>
<td>-</td>
<td>( 2.1(2.2)^c \pm 0.2^d )</td>
</tr>
<tr>
<td>1 - \cos(i) &lt; 0.3</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1 - \cos(i) &lt; 0.3 &amp; face-on corrected</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Spheroids (bulges + ellipticals) (a)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>uncorrected</td>
<td>-</td>
<td>( 2.7 \pm 0.4^d )</td>
</tr>
<tr>
<td>inclination corrected</td>
<td>-</td>
<td>( 2.1 \pm 0.3^d )</td>
</tr>
<tr>
<td>inclination &amp; face-on corrected</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>3.33 \times (1 - \cos(i) &lt; 0.3)</td>
<td>-</td>
<td>( 2.4 \pm 0.4^d )</td>
</tr>
<tr>
<td>3.33 \times (1 - \cos(i) &lt; 0.3) &amp; face-on corrected</td>
<td>-</td>
<td>( 3.1(3.2)^c \pm 0.4^d )</td>
</tr>
<tr>
<td>Ellipticals (no corrections)</td>
<td>-</td>
<td>( 0.8 \pm 0.1^d )</td>
</tr>
</tbody>
</table>

Net effect on ratios relatively minor (few %)
How dust affects structural params v inclination

Pastrav et al (2013)
See also:
Mollenhoff, Popescu & Tuffs (2003)
Wavelength dependence of size and Sersic index?

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Can measure LFs of Elliptical and non-elliptical systems

Correct non-ellipticals for dust using MGC photon escape fraction

Integrate LFs to get luminosity density

Observed energy output of the combined z=0 galaxy population

Driver et al (2012)
SED of Universe at $z=0$

Energy released into the IGM at $z=0$

- Spheroids
- Discs
- Total

Driver et al (2012)
SED of Universe at z=0

Unattenuated spectrum for spheroids and discs


Driver et al (2012)
SED of Universe at $z=0$

Missing energy transferred to dust

Energy released into the IGM at $z=0$

- Spheroids
- Discs
- Total

Dale & Helou (2002)

Driver et al. (2012)
SED of Universe at z=0

**PREDICTED** far-IR emission

Energy released into the IGM at z=0

- Spheroids
- Discs
- Total

Driver et al (2012)
SED of Universe at $z=0$

**PREDICTION** v FIR data

Driver et al (2012)
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Spheroids & Discs?

Are there 2 distinct evolutionary modes?

Hot mode $\rightarrow$ spheroids (collapse/mergers)

Cold mode $\rightarrow$ discs (accretion/gas infall)
AGN and Spheroid formation

e.g., near-IR relation from Vika et al (2012)

Richards et al (2007)
Two phase galaxy formation?

Axioms:

AGN activity traces spheroid formation (Richards et al 2007)
Spheroid formation dominates at high-z (Hopkins & Beacom 2006)

![Graph showing the relationship between SFR (M_☉ yr^-1 Mpc^-3 h_3^3) and Redshift. The graph includes data points for CSFH (Hopkins & Beacom 2006), AGN (Richards et al 2007), and SDSS+GALEX (Robotham & Driver 2011).]
Two phase galaxy formation?

Axioms:

AGN activity traces spheroid formation (Richards et al 2007)
Spheroid formation dominates at high-z (Hopkins & Beacom 2006)
Two phase galaxy formation?

Baldry & Glazebrook IMF
PEGASE2.0
Z(t) 0->Local

Driver et al (2013)
Prediction of bulge and disc mass

Mass prediction 50% too high (as for all models) but mass ratio agrees well with MGC i.e., 60%discs 40% spheroids
Implied transition redshift at $z \sim 1.5$

Hubble types:
- Ordered
- Symmetrical

Disc formation:
- Asymmetric
- Multiple-cored

Disturbed:
- Spheroid formation

Simon Driver & Alberto Fernandez-Soto (UNSW)
Galaxy Evolution?

- Collapse \((z<10+)\)
- Mergers/AGN \((1 < z < 8)\)
- Accretion \((1 < z < 2)\)
- Gas Infall \((z<1)\)
- Secular \((z<0.5)\)

Thick rotating discs (proto-Spheroids)

Turbulent discs (proto-Spheroids)

Compact spheroids

Minor Merging

Dynamical Relaxation

Adiabatic expansion

Evolution of structure
What does a spheroid look like while forming?

- A. a perfect spheroid but blue (i.e., violent collapse)
- B. a thick turbulent disc (i.e., merger->spheroid)
- C. a clumpy thick disc (i.e., clump migration->spheroid)
- D. all of the above!
- E. none of the above!!
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- C. a clumpy thick disc (i.e., clump migration --> spheroid)

Likely not to look like Ellipticals as SFR is vigorous

Lange et al (see poster)

Figures from Glazebrook (2013)
Legacy surveys

- SECULAR
- COLD: Accretion/Infall
- HOT: AGN/Spheroid formation

SFR (M_☉ yr⁻¹ Mpc⁻³ h₀⁻²)

- Spheroids
- Discs
- Combined
- HB06

Time since Big Bang (Gyrs)

z~1.5

SDSS
MGC

WAVES

MOONs

WAVES+JWST
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Key issues

• Which components are primary and which are secondary?
  – Primary: Spheroids (Ellipticals and classical bulges), disc, nucleus?
  – Secondary: Pseudo-bulges, bars, rings?

• How do we decide how many components to fit?
  – AIC, BIC, reduced $\chi^2$, eyeball over-ride?
  – Can we ever distinguish Es from S0s without dynamical info?

• Do we detect bulges or bulge complexes?
  – Sbc=pbulges, Sa=classical bulges, S0=both?
  – Sbc=pbulge dominant, Sa=classical bulge dominant, S0=either

• Structure is strongly wavelength and inclination dependent:
  – What wavelength do we fit in?
  – Simultaneous wavelength fitting: GALFIT-M/MEGAMORPH
  – Build stellar mass maps?