Formation and Evolution of Galaxy Bulges
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The Millennium Galaxy Catalogue: the severe attenuation of bulge flux by dusty spiral discs

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Abstract. Using the Millennium Galaxy Catalogue we quantify the dependency of the disc and bulge luminosity functions on galaxy inclination. Using a contemporary dust model we show that our results are consistent with galaxy discs being optically thick in their central regions ($\tau_B^f = 3.8 \pm 0.7$). As a consequence the measured B-band fluxes of bulges can be severely attenuated by 50% to 95% depending on disc inclination. We argue that a galaxy's optical appearance can be radically transformed by simply removing the dust, e.g. during cluster infall, with mid-type galaxies becoming earlier, redder, and more luminous. Finally we derive the mean photon escape fraction from the integrated galaxy population over the 0.1μm to 2.1μm range, and use this to show that the energy of starlight absorbed by dust (in our model) is in close agreement with the total far-IR emission.

Keywords. galaxies: bulges, galaxies: evolution, galaxies: formation, galaxies: fundamental parameters, galaxies: luminosity function, mass function

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1. Introduction

The issue of dust in galaxies has a long and heated history (Valenitjn 1990, Burstein *et al.* 1991, Disney *et al.* 1989). To summarise: Selection effects coupled with simplistic slab models played havoc with the interpretation of the available, but highly biased, galaxy samples. Ultimately it was agreed that one cannot use the available data to simultaneously constrain opacity and dust geometry and no clear consensus on opacity was reached. Certainly, from within the MW, one can see that our galaxy is optically thin away from the Galactic plane (we can see external galaxies), and is optically thick within it (the Galactic Centre is opague). However how the central region of our Galaxy would appear if viewed face-on is unclear. Observations of nearby spiral galaxies with a second spiral galaxy behind (e.g., White *et al.* 2000) suggest that, at least in the inter-arm region, galaxies are optically thin. This is corroborated by the number-counts of galaxies in inter-arm regions (Gonzalez *et al.* 1998). However this does not prove that galaxies are optically thin throughout (one can only reach that conclusion if one adopts a simplistic slab like model, e.g., Disney *et al.* 1989; Byun *et al.* 1993). Recently Driver *et al.* (2007) use a relatively new method to constrain the central face-on opacity of galaxies. This involves measuring the galaxy luminosity function (GLF) for face-on, inclined, and edge-on systems (see Fig. 1). In the absence of dust the measured GLFs should be identical. If galaxies are optically thick one expects edge-on systems to be severely attenuated and the measured GLF shifted to fainter magnitudes. The larger the shift the higher the central face-on opacity.

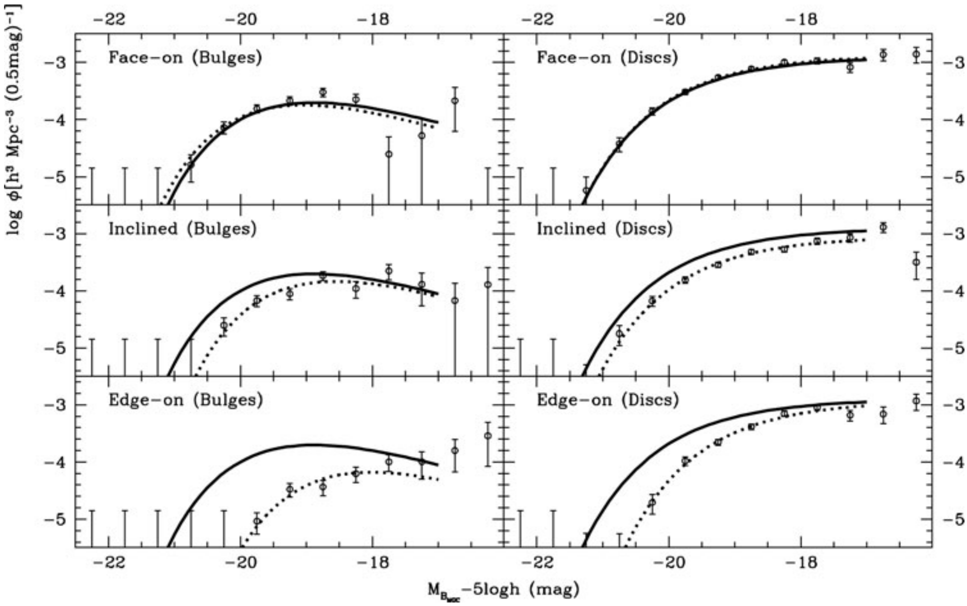

Figure 1. The galaxy luminosity function of bulges (left) and discs (right) for face-on (upper), inclined (centre), and edge-on (lower) systems.

The attenuation-inclination relation

Fig. 1 shows GLFs measured for bulges (left) and discs (right) drawn from face-on (top), inclined (centre), and edge-on systems (lower). Fig. 1 shows a significant trend of greater attenuation towards higher inclination. Fig. 2 summarises the attenuation-inclination relation for bulges and discs across the full inclination range (see Driver *et al.* 2007 for full details). The data shown in Fig. 1 & 2 has been derived from the Millennium Galaxy Catalogue (Liske *et al.* 2003) which contains 10,095 galaxies with full bulge-disc decompositions (Allen *et al.* 2006), and which has been shown to be robust to surface brightness selection bias to $M_B < -16$ mag (see Driver *et al.* 2005).

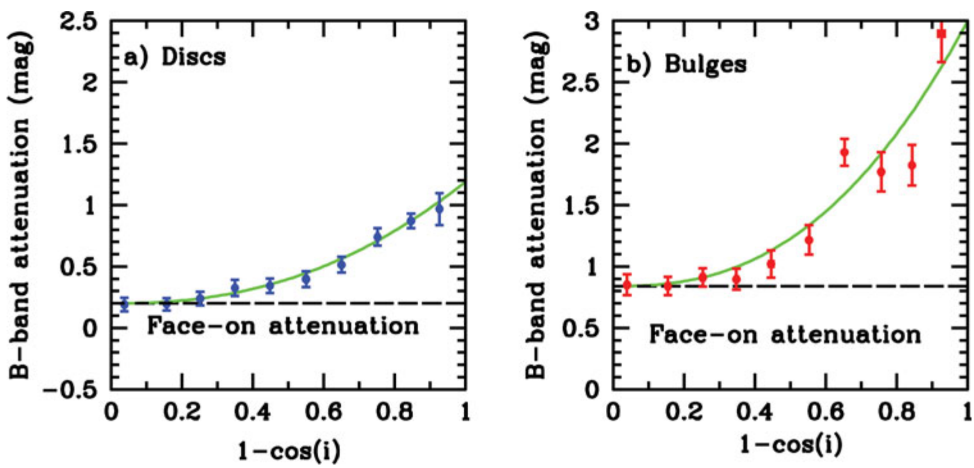

Figure 2. The empirical variation of the GLR turnover point for discs (left) and bulges (right) as a function of galaxy inclination. The face-on attenuation is model dependent, see text.

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To model the attenuation-inclination relation and derive the remaining face-on attenuation, we adopt the model of Popescu *et al.* (2000) and Tuffs *et al.* (2004) (see also Möllenhoff *et al.* 2006). This dust model incorporates three distinct components:
1. An optically thin dust distribution, similar to the traditional slab model.
2. A centrally concentrated dust distribution (ideally this would incorporate spiral density wave patterns to reflect the variation in opacity from arm to inter-arm regions)
3. A clumpy component to represent Giant Molecular Cloud regions.

The model incorporates 3D radiative transfer, forward, and backward scattering and realistic grain compositions and size distributions. These are a significant step forward over the simplistic slab models of the 90s and various studies have clearly demonstrated the need for this level of sophistication when modeling dust attenuation (Pierini *et al.* 2003). The modeling of the attenuation-inclination relation (Fig. 2) involves one free parameter, the mean central face-on opacity, as all other aspects of the model have been constrained via earlier multi-wavelenth observations of nearby galaxies. The implied central face-on opacity is $\tau_B^f = 3.8 \pm 0.7$ which implies that the central region of disc galaxies are, on average, optically thick. This will have serious consequences for flux measurements of galaxy bulges.

Implication for galaxy transformation

Based on the amount of dust we believe discs contain, Fig. 3 shows a cartoon of a mid-type galaxy with a centrally optically thick disc as it falls into a cluster. Simply by removing the dust, via some unspecified mechanism, the galaxy is transformed to an earlier, redder, and brighter system as the bulge is fully revealed and the disc fades. While it is unlikely that this process explains the entire transformation process from Sc to S0 it is undoubtedly part of the story and may mitigate the need for dry mergers.

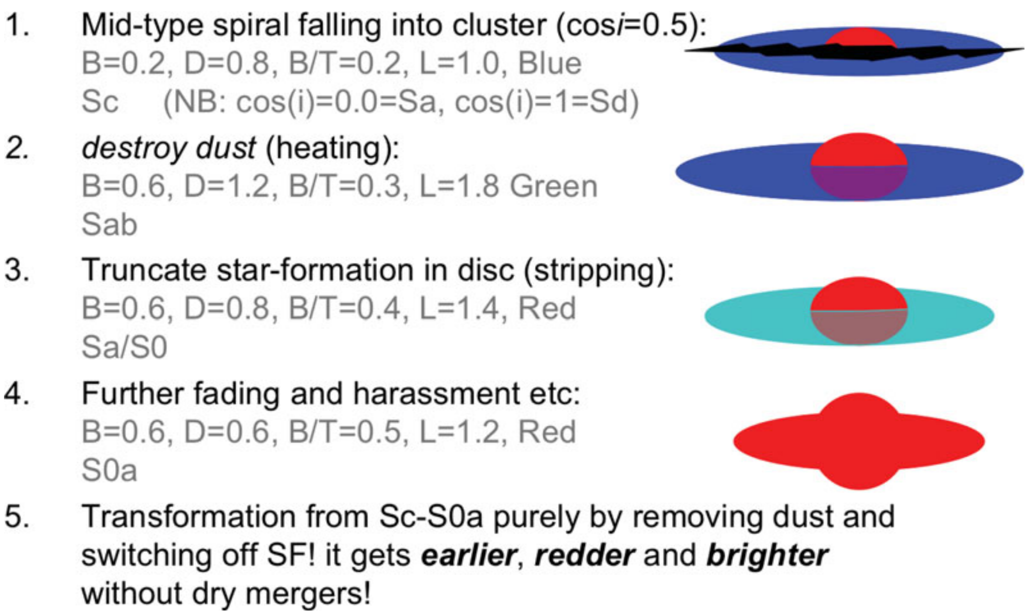

Figure 3. A schematic showing the possible fate of a mid-type spiral entering a cluster. B refers to bulge fraction, D to disc fraction and L to luminosity.

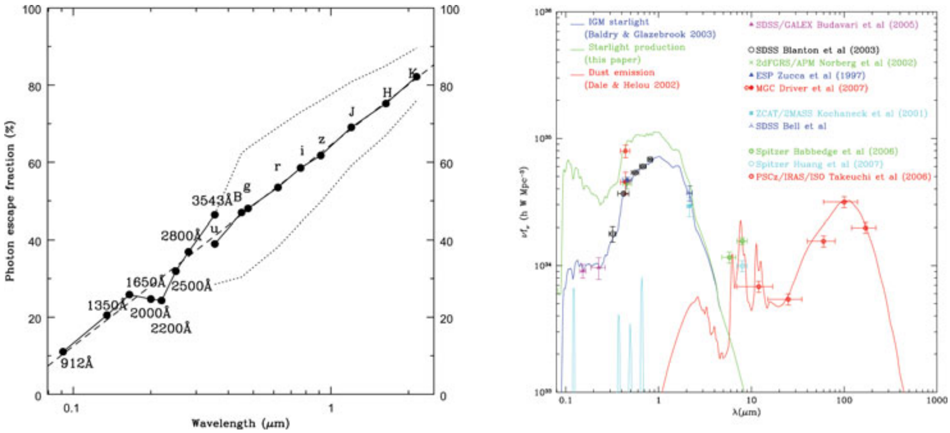

Figure 4. (Left) the fraction of photons which escape the galaxy population into the inter–galactic medium versus wavelength and (right) the cosmic spectral energy distribution showing the pre- (green), post- (blue attenuated starlight and the far-IR dust emission (red). Various data are shown as indicated.

The photon escape fraction and cosmic spectral energy distribution

In a forthcoming paper (Driver *et al.*, in prep) we use our dust model to derive the mean photon escape fraction versus wavelength (Fig. 4, left) integrated over the nearby galaxy population and demonstrate that the energy of starlight removed is consistent with the total far-IR radiation (Fig. 4, right).

Conclusions

1. In the *B*-band galaxy discs are optically thick in their central regions.
2. As a consequence total bulge flux can be attenuated by 0.8 to 2.5 mags depending on inclination (and wavelength).
3. Removing the dust from a mid- to late-type system, e.g., during cluster infall, will make a galaxy appear *significantly* earlier, redder, and brighter (in the *B*-band).
4. Estimates of the luminosity density of galaxies in the nearby Universe significantly underestimate the total luminosity density produced by the integrated stellar population.
5. The total energy of starlight absorbed equals the total far-IR emission (i.e., lost starlight = dust emission, 45% of all starlight (energy) is attenuated by dust.

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