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A *Herschel*★-ATLAS study of dusty spheroids: probing the minor-merger process in the local Universe

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ABSTRACT

We use multiwavelength (0.12–500 μm) photometry from *Herschel*-ATLAS, *WISE*, *UKIDSS*, *SDSS* and *GALEX* to study 23 nearby spheroidal galaxies with prominent dust lanes (DLSGs). DLSGs are considered to be remnants of recent minor mergers, making them ideal laboratories for studying both the interstellar medium (ISM) of spheroids and minor-merger-driven star formation in the nearby Universe. The DLSGs exhibit star formation rates (SFRs) between 0.01 and 10 $M_{\odot}$ yr^{-1}, with a median of 0.26 $M_{\odot}$ yr^{-1} (a factor of 3.5 greater than the average SG). The median dust mass, dust-to-stellar mass ratio and dust temperature in these galaxies are around $10^{7.6}$ $M_{\odot}$, ≈0.05 per cent and ≈19.5 K, respectively. The dust masses are at least a factor of 50 greater than that expected from stellar mass loss and, like the SFRs, show no correlation with galaxy luminosity, suggesting that both the ISM and the star formation have external drivers. Adopting literature gas-to-dust ratios and star formation histories derived from fits to the panchromatic photometry, we estimate that the median current and initial gas-to-stellar mass ratios in these systems are ≈4 and ≈7 per cent, respectively. If, as indicated by recent work, minor mergers that drive star formation in spheroids with $(\mathrm{NUV} - r) > 3.8$ (the colour range of our DLSGs) have stellar mass ratios between 1:6 and 1:10, then the satellite gas fractions are likely ≥50 per cent.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation – galaxies: interactions – galaxies: ISM.

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1 INTRODUCTION

Spheroidal galaxies (SGs) dominate the massive-galaxy census in the local Universe making them good laboratories for studying galaxy evolution at late epochs. While largely composed of old stars (e.g. Trager et al. 2000), recent work on SGs using ultraviolet (UV) photometry demonstrates widespread recent star formation (e.g. Kaviraj et al. 2007), which builds ≈20 per cent of their stellar mass after $z \approx 1$ (Kaviraj et al. 2008). A strong correspondence between blue UV colours and morphological disturbances suggests that the star formation is merger driven. However, the major-merger rate is far too low to satisfy the frequency of morphologically disturbed SGs, indicating that *minor* mergers (mass ratios < 1:3) with gas-rich dwarfs (Kaviraj et al. 2009, 2011) drives the star formation in these systems. SGs with prominent dust lanes (DLSGs) are a rare class of object, considered to be the remnants of *recent* minor mergers (Shabala et al. 2012, see also Hawarden et al. 1981; Oosterloo et al. 2002; Michel-Dansac et al. 2008; Sol Alonso, Michel-Dansac & Lambas 2010). These systems are good laboratories for studying both the interstellar medium (ISM) in SGs and the minor-merger process that dominates star formation in SGs at late epochs.

While a detailed study of DLSGs is a compelling project, given their rarity, large samples of these galaxies have traditionally not been available. However, Kaviraj et al. (2012, K12 hereafter) have recently performed a survey-scale study of DLSGs, drawn from the entire Sloan Digital Sky Survey Data Release 7 (SDSS DR7) (Abazajian et al. 2009) via the Galaxy Zoo (GZ) project (Lintott et al. 2008). The K12 dust lanes are extended features (comparable to the galaxy effective radii) and ideally require colour images for detection, since the lane alters the ambient colour more dramatically than the brightness. K12 have demonstrated that, compared to the average SG, DLSGs reside in lower density environments, exhibit bluer UV–optical colours, an order of magnitude higher incidence of AGN and disturbed morphologies even in the shallow (54 s exposure) SDSS images, indicating a recent merger. Neither the dust masses in the prominent lanes nor the ‘warm’ dust masses [calculated via *Infrared Astronomical Satellite* (*IRAS*) fluxes], show any correlation with galaxy luminosity or the age of the recent starburst, indicating that the dust has an external origin.

Notwithstanding the detailed treatment in K12, an accurate analysis of star formation and the ISM in DLSGs greatly benefits from a study involving *Herschel* (Pilbratt et al. 2010). For example, star formation rates (SFRs) in weakly star-forming systems like SGs cannot be reliably measured using SDSS Hα fluxes because the dominant sources of ionization are often AGN or evolved stars (e.g. Sarzi et al. 2006) and also because the 3 arcsecond spectroscopic fibre samples varying fractions of light in individual galaxies (corrections can be made for this, but are inherently uncertain). Similarly, since *IRAS* largely traces warm (>25 K) dust (e.g. Dunne & Eales 2001), previous studies based on *IRAS* data may not reflect the true ISM characteristics of nearby SGs. In this Letter, we combine far-infrared (FIR) photometry from *Herschel* with UV [*Galaxy Evolution Explorer* (*GALEX*); Martin et al. 2005; Gil de Paz et al. 2007], optical (SDSS; Abazajian et al. 2009), near-infrared [UKIRT Infrared Deep Sky Survey (UKIDSS); Lawrence et al. 2007] and mid-infrared [*Wide Field Infrared Sky Explorer* (*WISE*); Wright et al. 2010] data, to perform a panchromatic study of DLSGs with an unprecedentedly wide wavelength baseline (0.12–500 μm). The aims are to (a) study the physical properties of DLSGs (e.g. SFRs, dust masses, dust fractions) and (b) reconstruct the gas properties of the progenitor systems to improve our understanding of the minor-merger process.

This Letter is organized as follows. In Section 2, we briefly describe the original K12 sample, the *Herschel*-overlap subset of K12 galaxies that underpins this study and the methodology for deriving the physical properties of DLSGs using panchromatic photometric data. In Section 3, we present these derived properties and in Section 4, we reconstruct the gas properties of the progenitor systems. We summarize our findings in Section 5. Throughout, we use the Komatsu et al. (2011) cosmological parameters and present photometry in the AB magnitude system (Oke & Gunn 1983).

2 GALAXY SAMPLE AND PARAMETER ESTIMATION

The K12 sample is drawn from the entire SDSS DR7 (which covers 11 663 deg^2) through visual inspection of galaxy images via the GZ project. GZ is a unique tool that has used 300 000+ members of the public to morphologically classify, via visual inspection, the entire SDSS spectroscopic sample (≈1 million objects). GZ is uniquely powerful in its ability to identify *rare* objects such as mergers (Darg et al. 2010) and dust lanes (e.g. K12) that are best selected via visual inspection and has produced large samples of such objects that are ideal for followup using other facilities.

Briefly, 19 000 GZ galaxies at $z < 0.1$ were flagged as containing a dust lane by *at least* one GZ user (individual galaxies have 50+ classifications). Each galaxy in this sample was visually re-inspected by SK and YST to determine whether the galaxy really has a dust feature and to select systems with early-type morphology. This yields a final sample of 352 DLSGs, with a median z, absolute r-band magnitude and stellar mass of 0.04, −21.5 and $10^{10.8}$ M$_{\odot}$, respectively. To check completeness, 1000 random SDSS SGs were inspected by SK and YST to determine how many DLSGs were *not* identified as such by at least one GZ user. This test yielded no results. In other words *all* DLSGs are classified as such by at least one GZ user and the K12 sample is likely complete for systems with prominent dust lanes.

The DLSGs in this study are extracted by cross-matching the K12 objects with the Phase 1 and North Galactic Pole fields of the *Herschel*-ATLAS survey (H-ATLAS; Eales et al. 2010), a 550 deg^2 survey at 100–500 μm using *Herschel's* SPIRE (Griffin et al. 2010) and PACS (Poglitsch et al. 2010) instruments. We refer readers to Pascale et al. (2011) and Ibar et al. (2010) for details of the map making. These fields cover ≈50 per cent of the full H-ATLAS footprint and all DLSGs in these fields are detected at $>5\sigma$ at 250 μm (Rigby et al. 2011), with reliable optical counterparts to the sub-mm emission (Smith et al. 2011; Hoyos et al., in preparation; Valiante et al., in preparation). In addition, we leverage panchromatic data from several overlapping surveys. From UV to K-band, we exploit the ‘Galaxy and Mass Assembly’ project (Baldry et al. 2010; Robotham et al. 2010; Driver et al. 2011), that provides r-band-matched aperture photometry from *GALEX* (UV), SDSS (optical) and UKIDSS (near-infrared) (Hill et al. 2011). In the mid-infrared (3.4–22 μm), we exploit the *WISE* All-Sky Survey (Wright et al. 2010). The final DLSG sample comprises 23 galaxies, with a median redshift and stellar mass of 0.05 and $10^{10.9}$ M$_{\odot}$, respectively, and 20-filter photometry covering three orders of magnitude in wavelength (0.12–500 μm). Fig. 1 presents SDSS images of typical galaxies in our sample.

We estimate the physical properties of our DLSGs using the energy-balance technique of da Cunha, Charlot & Elbaz (2008, hereafter DC08) via the MAGPHYS code. Briefly, DC08 compute a library of model spectra, described by dust emission from stellar birth clouds (with contributions from polyaromatic hydrocarbons

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Figure 1. SDSS *gri* composite images of typical DLSGs in our study. Note the widespread morphological disturbances that are apparent even in the shallow (54 s exposure) SDSS images.

and hot [130–250 K], warm [30–60 K] and cold [15–25 K] grains) and match it to a second model library, generated using a wide range of stochastic star formation histories (SFHs), metallicities and dust attenuations. The matching is performed by assuming that the energy absorbed by dust (described by the second library) is re-emitted in the infrared wavelengths (described by the first library). Stellar populations are modelled using the latest version of the Bruzual & Charlot (2003) stellar models, with dust attenuation calculated using Charlot & Fall (2000). We refer readers to DC08 for full details of the method. The properties of individual galaxies are estimated by comparing their observed multiwavelength photometry to the matched DC08 model spectra and extracting marginalized probability density functions (PDFs) for parameters of interest – e.g. stellar masses, SFRs (averaged over the last 10^7 yr) and dust masses – from which median likelihood estimates can be calculated. Note that the 20-band (UV to FIR) wavelength baseline employed here significantly improves the accuracy of the derived parameters compared to all previous studies of DLSGs.

3 PHYSICAL PROPERTIES OF SPHEROIDS WITH DUST LANES

We begin by discussing the physical properties of our DLSGs. Fig. 2 (inset) indicates that the median (NUV − *r*) colour of these systems is ≈0.5 mag bluer than the general SG population (in the same redshift and mass range), due to star formation. The SFRs in these systems (Fig. 2, main panel) span the range 0.01–10 $M_{\odot}$ yr^{-1}, with a median value of ≈0.26 $M_{\odot}$ yr^{-1}, which is a factor of 3.5 greater than that in the general SG population (Rowlands et al. 2012). Fig. 3 presents the derived dust properties of our DLSGs. We show stacked PDFs for the DLSG population as a whole, calculated by summing the marginalized parameter PDFs for individual galaxies and normalizing by the total number of DLSGs. The median dust mass in these systems is around $10^{7.6}$ $M_{\odot}$, an order of magnitude higher than the typical (*Herschel*-derived) dust mass in the general SG population (see Rowlands et al. 2012; Smith et al. 2012). The median dust temperature is ≈19.5 K and the typical dust-to-stellar mass ratio is ≈0.05 per cent.

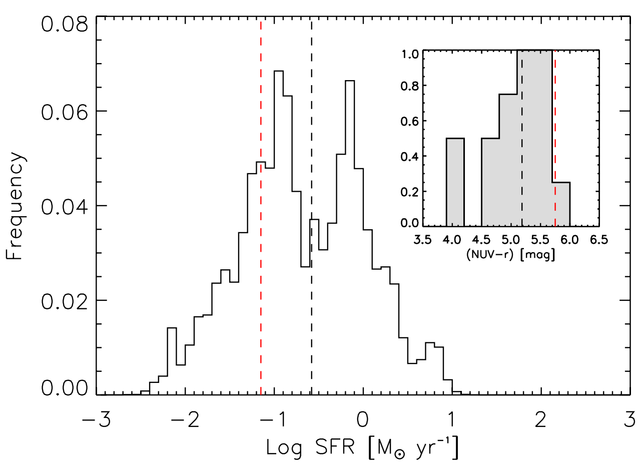

Figure 2. Main panel: DLSG SFRs, estimated using panchromatic (0.12–500 μm) photometry. The black and red dashed lines indicate median values for the DLSGs and the general SG population (Rowlands et al. 2012), respectively. Inset: the (NUV − *r*) colours of the DLSGs. The black and red dashed lines indicate median values for the DLSGs and the general SG population (Kaviraj et al. 2007), respectively.

In the bottom-right panel of Fig. 3, we show the ratio of the dust mass in the prominent dust lanes (calculated by K12) to the total dust mass (measured using our multiwavelength analysis). Briefly, the dust mass in the lanes is calculated as follows. For each galaxy, ellipses are fitted to isophotes in the SDSS *r*-band image (with the dust features masked out), using the IRAF task ELLIPSE. For each galaxy, an extinction map is constructed using the ratio of the observed flux and the flux in the model fit (calculated by fitting ellipses to the SDSS *r*-band image with the dust features masked out). The Galactic mass absorption coefficient is then used to calculate the dust mass that resides in the large-scale features. We refer readers to section 6.1 of K12 for details of this method. Fig. 3 indicates that the dust fraction hosted by the prominent dust lanes in these systems is remarkably small, between 1/10 and 1/500 of the total dust mass (with a median value of ≈1/50, i.e. ≈2 per cent).

We explore the origin of the dust in our DLSGs in Fig. 4. The top panel shows that there is no correlation between the total dust masses and absolute *r*-band magnitudes of our galaxies. By contrast, the dust masses in spiral galaxies correlate well with their luminosities (indicating an internal origin). Our results remain the same regardless of the optical filter used. Note that the DLSG SFRs also show a similar lack of correlation with absolute magnitude (not shown). In the bottom panel of Fig. 4, we plot the distribution of the 'dust excess' in individual DLSGs, defined as the difference between the total dust mass and the maximum dust mass expected from internal stellar mass loss. The mass-loss contribution is estimated using the blue luminosity following Merluzzi (1998; see their fig. 1) and assumes dust depletion via sputtering in the hot gas over a maximal destruction time-scale of $10^{7.5}$ yr (see e.g. Draine & Salpeter 1979; Dwek, Rephaeli & Mather 1990), although it is worth noting here that empirical dust depletion rates have not been extensively studied in SGs. The dust masses in our DLSGs are at least a factor of 50 greater than the dust mass expected from stellar mass loss. Taken together, these results argue against an internal origin for the dust content and indicate that both the ISM and star formation in these galaxies have *external* drivers. The widespread morphological disturbances further suggest that this driver is indeed a recent merger. It is worth noting here that DLSGs inhabit low-density environments (only 2 per cent of the K12 sample are in clusters). The *Herschel*-detected DLSGs in this Letter exclusively inhabit the field, so that environmental processes like ram-pressure stripping of the ISM are likely to be absent in these galaxies.

4 GAS PROPERTIES OF THE PROGENITOR (MINOR) MERGERS

Given the significant role of minor mergers in driving star formation in massive galaxies at late epochs (e.g. Kaviraj et al. 2011), empirical constraints on the gas properties of these minor mergers

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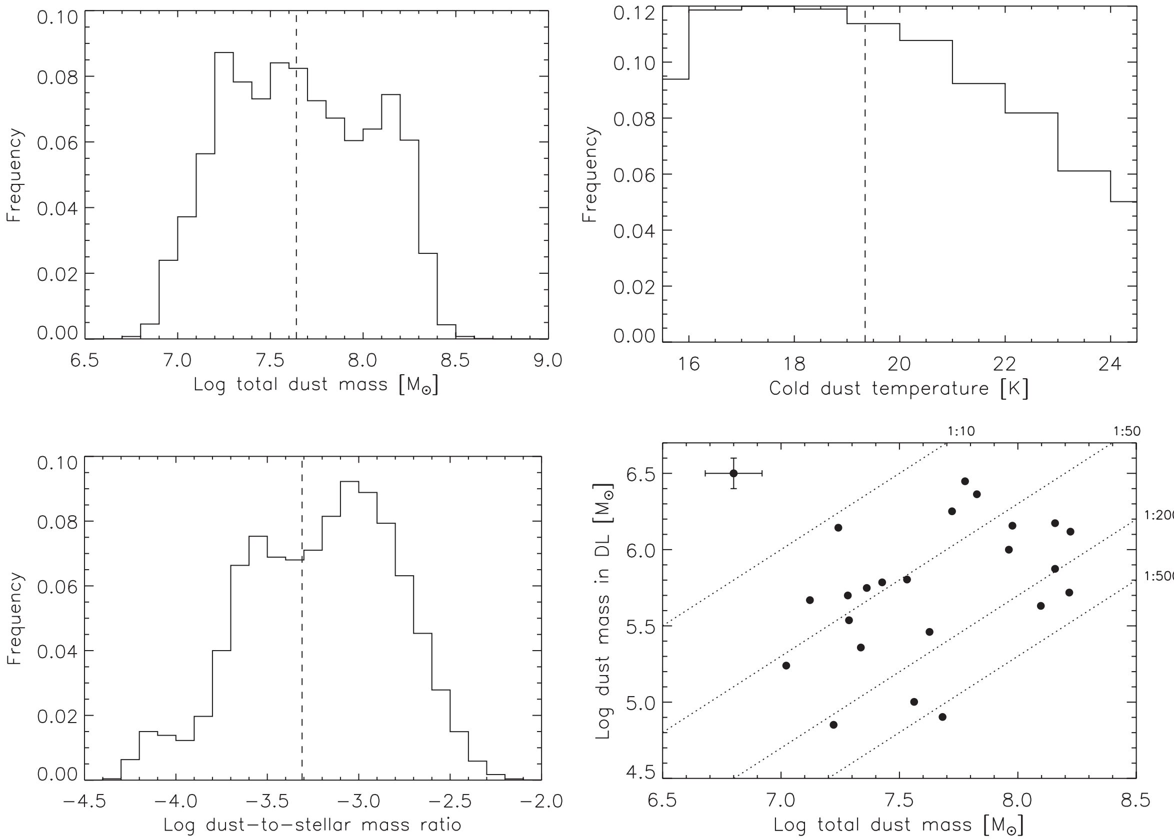

Figure 3. Total dust mass (top left), cold dust temperature (top right), dust-to-stellar mass ratio (bottom left) and dust mass hosted by the dust lanes versus total dust mass (bottom right). Dashed lines indicate median values. The dotted lines in the bottom-right panel indicate constant mass ratios. The histograms are stacked PDFs for the DLSG population as a whole (see text for details).

are desirable but remain scant. Our DLSGs offer an opportunity to explore these properties, in particular the gas fractions of the satellites that fuel star formation in massive galaxies at late epochs. While this was explored in K12, the significantly higher quality of both the data and the derived dust properties in this study allows us to reconstruct the gas fraction of the progenitor systems of our DLSGs with better accuracy.

We begin by estimating the *current* gas-to-stellar mass ratios in our DLSGs, using recently measured gas-to-dust (G/D) ratios in SGs, that involve *Herschel*-derived dust masses. Note that ‘gas’ refers to the sum of the atomic (H I) and molecular (H_2) gas masses. In Cen A – the archetypal SG with a dust lane and a system that is similar to our DLSGs – Parkin et al. (2012) calculate a G/D ratio of 103 ± 8. The equivalent values in nearby SGs from the *Herschel* Reference Survey (which do not have prominent dust lanes) lie in the range 120 ± 24 (Smith et al. 2012). The values measured so far thus appear to lie within a reasonably small range (≈100 to 150) and close to the canonical Milky Way value of 150 (Spitzer 1978; Draine & Lee 1984), regardless of whether the SG in question hosts a prominent dust lane. This appears consistent with the fact that only a small fraction of the total dust mass is hosted by the dust lanes themselves. Using a mean G/D ratio of 120, then yields *current* gas-to-stellar mass ratios in our DLSGs between 1 and 20 per cent, with a median of ≈4 per cent. As star formation is clearly ongoing in these systems, these gas-to-stellar mass ratios are lower than the *initial* ratios in the progenitor systems.

Since the native cold gas in SGs is negligible and incapable of driving the observed UV colours of our DLSGs (see e.g. Kaviraj et al. 2007), and given the evidence for the ISM having an external origin, it is reasonable to assume that the gas in the progenitor system is provided by the accreted satellite. We conclude this section by estimating the initial gas-to-stellar mass ratios of the DLSGs and the gas fractions of satellites that are fuelling their star formation.

Detailed numerical simulations (see Kaviraj et al. 2009) indicate that SGs with $NUV - r > 3.8$ (the colour range spanned by our DLSGs) are likely remnants of mergers with mass ratios between 1:6 and 1:10 and that the induced star formation is typically complete within ≈3 Gyr (largely independent of mass ratio). Thus, the initial gas-to-stellar mass ratio can be estimated by integrating the MAGPHYS-derived SFH of each DLSG over the last 3 Gyr, adding this to the current gas mass and dividing by the stellar mass of the system. Fig. 5 presents these initial gas-to-stellar mass ratios, with the dashed line indicating the median value (≈7 per cent). Finally, given mass ratios between 1:6 and 1:10, a median gas-to-stellar mass ratio of ≈7 per cent implies that the gas fractions in the satellites accreted by our DLSGs were likely to be high, between 50 and 80 per cent.[1] Note that, given the assumptions employed in deriving these estimates, the values are only indicative – a more accurate analysis of the gas properties can be achieved using longer wavelength follow up of the DLSGs, using facilities such as the IRAM radio telescope and the Atacama Large Millimetre Array.

[1] If g is the system gas mass and m and M are the stellar masses of the satellite and spheroid, then the initial gas-to-stellar mass ratio (k) is: $k = \frac{g}{m+M}$. Assuming the satellite donates the gas then the satellite gas fraction is $\frac{g}{m} = k \times (1 + \frac{M}{m})$.

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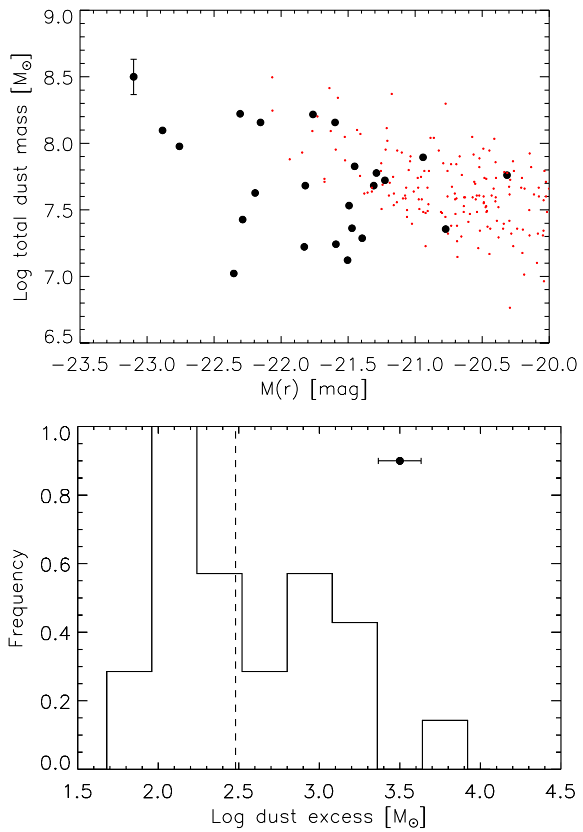

Figure 4. Top: total dust mass versus $M(r)$. Black circles are DLSGs and small red circles indicate spirals. Bottom: distribution of dust excess in our DLSGs, defined as the difference between the total dust mass and that expected from stellar mass loss. The median value is indicated by the vertical dashed line.

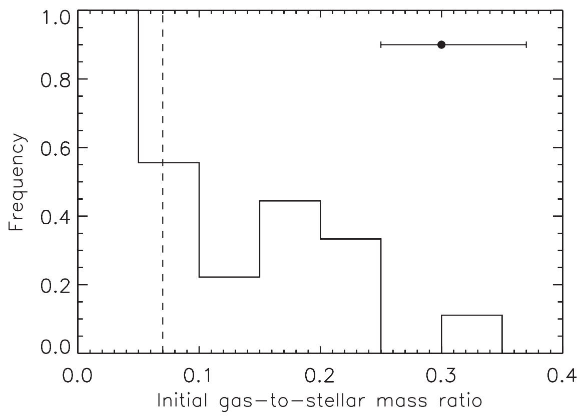

Figure 5. Initial gas-to-stellar mass ratios in the progenitor systems of our DLSGs (see text in Section 4 for details). The median value is indicated by the vertical dashed line.

5 SUMMARY

We have studied 23 local ($\langle z \rangle \approx 0.05$), massive ($\langle M_* \rangle \approx 10^{10.9}\,\mathrm{M}_\odot$) DLSGs, drawn from the SDSS DR7 via visual inspection using the GZ project. The DLSGs studied here have 20-band (0.12–500 μm) photometric data from the H-ATLAS (FIR), *WISE* (mid-infrared), UKIDSS (near-infrared), SDSS (optical) and *GALEX* (UV) surveys, allowing us to probe the properties of their ISM and star formation in unprecedented detail. DLSGs are known to be the remnants of recent *minor* mergers between spheroids and gas-rich dwarfs – given the important contribution of minor mergers in driving cosmic star formation at late epochs, these systems are, therefore, unique laboratories for studying both the ISM of spheroids and the minor-merger process in the local Universe.

Our DLSGs are ≈0.5 mag bluer in the (NUV $-$ r) colour than the general SG population, due to enhanced star formation. The SFRs span a large range (0.01–10 $\mathrm{M}_\odot\,\mathrm{yr}^{-1}$), with a median value of 0.26 $\mathrm{M}_\odot\,\mathrm{yr}^{-1}$. The median dust mass is $\approx 10^{7.6}\,\mathrm{M}_\odot$, an order of magnitude greater than the typical dust mass in the average SG. The median dust-to-stellar mass ratio is ≈0.05 per cent and the typical dust temperature is ≈19.5 K. The dust hosted by the prominent dust lanes is remarkably small, between 1/10 and 1/500 (with a median of 1/50) of the total dust mass in the system. The dust masses and SFRs show no correlation with galaxy luminosity and the dust masses are at least a factor of 50 greater than the contribution expected from stellar mass loss. Taken together, this indicates an external origin and driver for the ISM and star formation in these systems.

The DLSGs offer a route for estimating the gas properties of the minor mergers that drive star formation in massive galaxies in the nearby Universe. Using literature G/D ratios, the *current* gas-to-stellar mass ratios in these systems are estimated to be between 1 and 20 per cent, with a median value of 4 per cent. Combining these current ratios with SFHs derived using panchromatic (0.12–500 μm) photometry, we have estimated the *initial* gas-to-stellar mass ratios in the progenitor systems of our DLSGs to be <30 per cent, with a median value of 7 per cent. If – as suggested by recent work – the mass ratios of minor mergers that induce star formation in SGs with (NUV $-$ r) > 3.8 is between 1:6 and 1:10, then the gas fractions of the satellites accreted by our DLSGs were likely to be >50 per cent.

In forthcoming work, we will further probe the properties and external origin of the ISM in these systems e.g. by using IRAM to derive accurate G/D ratios which correlate with the gas-phase metallicity and using integral-field spectroscopy to trace kinematical misalignments between the gas and stars, which would be expected if the gas is accreted from an external source.

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