Circumstellar dust, PAHs and stellar populations in early-type galaxies: insights from GALEX and WISE

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ABSTRACT
A majority of early-type galaxies contain interstellar dust, yet the origin of this dust, and why the dust sometimes exhibits unusual polycyclic aromatic hydrocarbon (PAH) ratios, remains a mystery. If the dust is internally produced, it likely originates from the large number of asymptotic giant branch stars associated with the old stellar population. We present GALEX and WISE elliptical aperture photometry of ~310 early-type galaxies with Spitzer mid-infrared spectroscopy and/or ancillary data from ATLAS3D, to characterize their circumstellar dust and the shape of the radiation field that illuminates the interstellar PAHs. We find that circumstellar dust is ubiquitous in early-type galaxies, which indicates some tension between stellar population age estimates and models for circumstellar dust production in very old stellar populations. We also use dynamical masses from ATLAS3D to show that WISE W1 (3.4 μm) mass-to-light ratios are consistent with the initial mass function variation found by previous work. While the stellar population differences in early-type galaxies correspond to a range of radiation field shapes incident upon the diffuse dust, the ratio of the ionization-sensitive 7.7 μm/11.3 μm PAH feature does not correlate with the shape of the radiation field, nor to variations with the size-sensitive 11.3 μm/17 μm ratio. The 7.7 μm/11.3 μm PAH ratio does tend to be smaller in galaxies with proportionally greater H$_2$ emission, which is evidence that processing of primarily smaller grains by shocks is responsible for the unusual ratios, rather than substantial differences in the overall PAH size or ionization distribution.

Key words: galaxies: elliptical and lenticular, cD – galaxies: stellar content – infrared: galaxies – ultraviolet: galaxies.

1 INTRODUCTION
While early-type galaxies (ETGs) were historically associated with uniformly old stellar populations and no cold interstellar medium (ISM), 40 years of multiwavelength observations have demonstrated that view as too simplistic. Instead, many ETGs have a complex, multiphase ISM, often with a mixture of cold (Knapp, Turner & Cunniffe 1985; Wardle & Knapp 1986), warm (Caldwell 1984; Phillips et al. 1986; Sadler 1987), and hot (Forman, Jones & Tucker 1985; Canizares, Fabbiano & Trinchieri 1987) gas. Improved angular resolution has also led to the detection of dust lanes in many ETGs (Sadler & Gerhard 1985; Sparks et al. 1985; Ebneter, Davis & Djorgovski 1988; Veron-Cardy & Veron 1988; Goudfrooij et al. 1994), and observations in the far-infrared (FIR) indicated that many ETGs contain a diffuse, cold dust component (Jura et al. 1987; Knapp et al. 1989; Goudfrooij & de Jong 1995; Bregman et al. 1998). Mid-infrared (MIR) observations from the Infrared Space Observatory (ISO) satellite found flux in excess of expectations for the stellar population of many ETGs, which was postulated to arise from either polycyclic aromatic hydrocarbon (PAH) or very small grain (VSG) emission (Madden, Vigroux & Sauvage 1999; Ferrari et al. 2002; Padre et al. 2004; Xilouris et al. 2004). The existence of these small grains was surprising because of their short lifetimes in hot plasma (Draine & Salpeter 1979; Dwek & Arendt 1992), and so the origin of these grains is hotly debated.

MIR spectroscopy of individual PAH features in ETGs indicated that the relative strengths of short-wavelength and long-wavelength PAH features were often vastly reduced compared to the same features in star-forming galaxies (Kaneda, Onaka & Sakon 2005). Proposed physical conditions which could lead to the relatively weaker short-wavelength features include a grain population dominated by neutral rather than ionized PAHs, and a larger grain size distribution compared to star-forming galaxies (Draine & Li 2007).

An explanation for both the existence of PAHs and their anomalous line ratios in ETGs has proven elusive. Kaneda et al. (2008) found that PAH emission is uncorrelated with stellar emission, and suggested that larger neutral PAHs were externally accreted through

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mers. Alternatively, Vega et al. (2010) posited that PAHs are produced by carbon-stars formed in a minor star-forming event, and that shocks with the ambient ISM then preferentially destroyed the small grains.

For galaxies without interstellar dust, we get a direct view of the MIR emission of the stellar population, which makes these galaxies well suited to test stellar population synthesis (SPS) models. They are representative of old stellar populations with little ongoing star formation (Yi et al. 2005; Kaviraj et al. 2007; Temi, Brighenti & Mathews 2009; Shapiro et al. 2010), and negligible extinction due to dust. We will use them to test stellar models for the evolved giant stars that dominate their light, especially the substantial progress on the thermally pulsating asymptotic giant branch (TP-AGB) phase over the last decade (Marigo et al. 2008, 2013; Girardi et al. 2010; Cassarà et al. 2013; Rosenfield et al. 2014). This phase is critical as the stars can contribute a significant amount of the integrated flux in the infrared (Maraston 2005; Kelson & Holden 2010; Melbourne et al. 2012; Conroy 2013; Melbourne & Boyer 2013).

Previous studies of AGB stars have shown that circumstellar dust is necessary to adequately describe their spectra in the MIR (Bedijn 1987; Trams et al. 1999; van Loon et al. 1999). However, the inclusion of circumstellar dust within SPS models has been difficult, and only a few models incorporate dusty AGB stars into their spectral libraries (Bressan, Granato & Silva 1998; Silva et al. 1998; Marigo et al. 2008; Villaume, Conroy & Johnson 2015). The expansion of MIR observations provide new opportunities to compare these circumstellar dust models to real stellar populations (e.g. Norris et al. 2014; Villaume et al. 2015).

It is difficult to compare circumstellar dust models to data in active star-forming galaxies because the circumstellar dust emission is often dwarfed by emission from dust in the diffuse ISM. For our sample of passive ETGs with much less interstellar dust, the circumstellar component can be observed in the MIR (beyond about 10 μm). Excess flux associated with circumstellar dust has been identified in a number of studies of galaxies without evidence for interstellar dust (Bressan, Granato & Silva 1998; Athey et al. 2002; Martini, Dicken & Storchi-Bergmann 2013).

The MIR region from 3 to 5 μm dominated by photospheric emission is valuable for stellar mass measurements. Since low-mass stars contain most of the stellar mass of a galaxy, observations at these wavelengths are more robust to variations in metallicity, star formation history (SFH), and star formation rate (SFR; Meidt et al. 2014). Results from SPS models have traditionally been the only way to measure the stellar masses of large numbers of galaxies. Alternative mass estimates were recently released by ATLAS 3D for a volume-limited sample of 260 ETGs closer than 42 Mpc with \( M_\star \gtrsim 6 \times 10^8 M_\odot \). Cappellari et al. (2013) derived dynamical masses for these galaxies using \( r \)-band photometry, SAURON integral-field unit (IFU) spectroscopy, and dynamical models based on the Jeans equations. They then obtained stellar masses by subtracting a Navarro–Frenk–White (NFW) halo; which yielded stellar masses with assumptions independent from SPS models.

We use MIR data from the WISE satellite, which observed the entire sky in four MIR bands: W1 (3.4 μm), W2 (4.6 μm), W3 (12 μm), and W4 (22 μm); see Wright et al. (2010) for further details. The first two bands are similar to the Spitzer Infrared Array Camera (IRAC) [3.6] and [4.5] bands, and the W4 band is similar to the Multiband Imaging Photometer for Spitzer (MIPS) 24 μm band. In typical galaxies, the W1 and W2 bands are expected to trace the evolved stellar population; the W3 band will contain significant PAH features; and the W4 band will be dominated by continuum emission from hot dust grains (e.g. Jarrett et al. 2013). Because of the all-sky coverage of WISE, all sufficiently bright ETGs can be studied in the MIR, a substantial increase over previous targeted surveys. This wide coverage will yield valuable demographic data about the stellar populations, circumstellar dust, and PAHs in ETGs, as well as identify promising targets for future study with targeted missions.

We also include UV photometry from the GALEX satellite to measure the shape of the radiation field incident on any PAHs that may be present. GALEX observed 63 per cent of the sky to a depth of at least \( m_{AB} = 20 \) mag in the FUV (1516 Å) and NUV (2267 Å) bands, with a resolution of about 4.25 and 5.25 arcsec, respectively (see Martin et al. 2005; Morrissey et al. 2005 for further details).

In this paper, we distinguish between ‘interstellar’ and ‘circumstellar’ dust as follows: ‘circumstellar’ dust resides within the stellar winds of AGB stars while ‘interstellar’ dust resides within the diffuse ISM. Circumstellar dust is intrinsically connected to the stellar population, which makes it a valuable extension to SPS models. Meanwhile, interstellar dust is often uncorrelated with the stellar population and usually dominates the IR emission when it is present.

Our paper is organized as follows. The next section of this paper contains a description of our samples of ETGs. Section 3 describes how we performed aperture photometry on both WISE and GALEX images and how we distinguish between galaxies with and without diffuse dust. In Section 4, we calculate stellar mass-to-light ratios for W1 from ATLAS 3D dynamical masses and compare them to mass-to-light ratios predicted by SPS models. We also compare models of circumstellar dust to our data, and use these to jointly constrain stellar ages and the masses of stars that produce circumstellar dust, as well as investigate the extent to which circumstellar dust can contaminate measurements of the SFR as measured from MIR indicators. Section 5 combines GALEX and WISE photometry with Spitzer Infrared Spectrograph (IRS) spectroscopy from previous works to investigate the properties of PAHs and their environments in ETGs. We also comment on the use of WISE photometry to determine the MIR properties of ETGs. We summarize our results in Section 6.

2 SAMPLES

We use MIR and UV photometry to study circumstellar and interstellar dust in ETGs. Our sample is drawn from two recent, comprehensive studies of ETGs: the characterizations of interstellar dust in ETGs with Spitzer-IRS spectra (Rampazzo et al. 2013), and the stellar population and dynamical study from the ATLAS 3D survey.

2.1 RSA Spitzer-IRS atlas

The Revised Shapley-Ames (RSA) catalogue is a canonical collection of bright, well-studied, nearby galaxies. Rampazzo et al. (2013) constructed their RSA Spitzer-IRS atlas by cross-matching the E–S0 galaxies from the RSA catalogue with Spitzer-IRS observations available in the Spitzer Heritage Archive (SHA). This sample consists of 91 ETGs, including 56 E-type, 27 S0-type, and 8 mixed E/S0+S0/E-type galaxies; their properties are given in Table 1. Rampazzo et al. (2013) uniformly reprocessed and analysed all of these spectra and measured line intensities for each of the detected emission lines.

Rampazzo et al. (2013) classified galaxies according to the Panuzzo et al. (2011) classification scheme for MIR spectra. A summary of the classification scheme is as follows: Class-0 galaxies are completely passive, that is apart from a few broad circumstellar dust features (Bressan et al. 1998), they have no emission lines in the
MIR. These galaxies have spectra consistent with only an old stellar population. Class-1 galaxies have emission features in their spectra, but no PAH features. Class-2 and Class-3 galaxies are those with anomalous and normal PAH features, respectively; they will be the primary focus of this work. Finally, Class-4 galaxies have a hot dust continuum.

### 2.2 The ATLAS3D sample

The ATLAS3D project surveyed a volume-limited sample within 42 Mpc of morphologically selected ETGs with $M_K < −21.5$ mag (Cappellari et al. 2011). This sample contains 260 ETGs: 68 E galaxies and 192 S0 galaxies (see Table 1). The extensive data available for the ATLAS3D sample includes Sloan Digital Sky Survey (SDSS) ugriz photometry (Abazajian et al. 2009; Scott et al. 2013), observations with the SAURON IFU spectrograph (Cappellari et al. 2011), 21 cm emission observations (Serra et al. 2012), and 12CO $J = 1−0$ and $J = 2−1$ observations (Altaloro et al. 2013). These data are available from the ATLAS3D website.1

The data collected for the ATLAS3D sample, combined with extensive dynamical and stellar population modelling, has resulted in a wealth of valuable measurements. Some relevant observational results include the presence of optical dust features (Krajnović et al. 2011), surface brightness profiles (Scott et al. 2013), and luminosities in the r band (Cappellari et al. 2013). We use their stellar population parameters derived from both SSP models and reconstructed SFH models (McDermid et al. 2015) to evaluate circumstellar dust models.

Finally, the dynamical analysis and modelling by Cappellari et al. (2013) include dynamical mass-to-light ratios derived by fitting models ($v_{max}$)1/2 to $V_{circ}$ measurements. These were derived from Jeans Anisotropic Multi-Gaussian Expansion (JAM) modelling (Cappellari 2008). The output from these fits include stellar mass-to-light ratios derived by simultaneously fitting an NFW halo (Navarro, Frenk & White 1996) and a separate stellar distribution constrained by the observed surface brightness profile (Cappellari et al. 2013).

### 3 DATA PROCESSING

We chose to perform all aperture photometry with the standard aperture used by the Two Micron All Sky Survey (2MASS) Extended Source Catalog (XSC);2 the $K_s = 20$ mag arsec$^{-2}$ isophote (hereafter K20). This isophote corresponds roughly to $1\sigma$ of the typical background noise in the $K_s$-images. Despite the fact that the K20 isophote under-represents the ‘total’ flux by $~10$–$20$ per cent, it provides the most reproducible measurement of a galaxy’s flux.3 There are also 2MASS JHK$_s$ measurements of the entire sample in this same aperture. The sizes of apertures for selected galaxies as shown in Fig. 1.

Because of point spread function (PSF) differences between the 2MASS and WISE surveys, the effective shape of the aperture needs to be corrected in order for the isophotes in the different beams to match.4 Because the WISE W4 beam is larger and more circular than the beams for the other three WISE bands, the W4 aperture is a different size and shape from the rest. For all but three objects, this adjustment was performed by the WISE pipeline, which generates a corrected aperture any time a 2MASS XSC object is centred within 2 arcsec of the WISE source. For the three objects whose centres in the two surveys are separated by more than 2 arcsec, we generated a matched aperture manually. We calculated these apertures by binning the ATLAS3D sample by 2MASS axis ratio, and interpolated the adjusted WISE semimajor axis and axis ratio to the object. GALEX apertures were not adjusted because the PSF differences are less important. The photometry parameters for all of the galaxies in our sample are given in Table 1.

### 3.1 WISE

We measured aperture photometry on the WISE Atlas images. These are co-added images available as high-level data products. The details of the image construction and calibration are described in the WISE explanatory supplement.5

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1 http://www-astro.physics.ox.ac.uk/atlas3d/

2 http://www.ipac.caltech.edu/2mass/releases/allsky/

3 http://www.ipac.caltech.edu/2mass/releases/allsky/doc/sec4_5a5.html

4 http://wise2.ipac.caltech.edu/docs/release/allsky/expsup/sec4_4c.html#ssc

5 http://wise2.ipac.caltech.edu/docs/release/allsky/expsup/index.html
There are presently two recommended data releases: All-Sky and AllWISE. The AllWISE release is more precise and sensitive because it incorporates observations from the post-cryo mission into the standard mission observations, among other improvements. However, inclusion of post-cryo observations decreases the saturation limit of the images, and hence decreases accuracy for bright objects. We therefore used All-Sky images for objects with saturated pixels, and otherwise used AllWISE. The data release of each image is included in Table 1.

We measured elliptical aperture photometry with the ELLIPSE package in IRAF using the adjusted K20 parameters given in Table 1. Sky values were estimated via the FITSKY package in IRAF. The inner radius of the annulus was chosen to be 1.5 times the semi-major axis of the photometric aperture in order to exclude galaxy flux. The thickness of the annulus was chosen to be 30 pixels in order to provide sufficient sky pixels to adequately measure the background.

We used SExtractor (Bertin & Arnouts 1996) to detect and mask foreground sources in the WISE W1 Atlas images, and then applied the masks to all four WISE bands. The most reliable method of foreground removal is PSF subtraction, as done in Jarrett et al. (2013). However, this method is not feasible for our large sample of galaxies due to the spatially variable PSF in the atlas images. Since the stellar emission in ETGs is morphologically smooth, foreground stars bright enough to significantly affect the galaxy’s flux are easily identified by SExtractor.

We also analysed the 17 galaxies (including three ellipticals) from Jarrett et al. (2013) in order to test our pipeline. We excluded the M51 pair because none of our targets requires similarly complex deblending. After comparing the flux measured from our pipeline...
to those reported by Jarrett et al. (2013), we encounter rms differences of W1: 0.05 mag, W2: 0.06 mag, W3: 0.12 mag, and W4: 0.07 mag; we adopt these values as estimates of our photometric uncertainties. Since the Jarrett et al. (2013) sample is more morphologically complex than our measurements, we expect these differences are upper limits to the true photometric uncertainties. These differences cannot be explained by colour corrections, which only correspond to 1 per cent differences. Our measurements for the full sample are provided in Table 2, and have not been corrected for extinction. The uncertainties in Table 2 are formal uncertainties, and include zero-point uncertainties of 0.006, 0.007, 0.015, and 0.012 mag for W1, W2, W3, and W4, respectively. For our analysis, we apply extinction corrections for 2MASS and WISE bands from Indebetouw et al. (2005).

3.2 GALEX

The GALEX GR6/7 data release has images from six different observing programs with varying breadths and depths. The deepest is the targeted GII program, followed by several science surveys. The surveys vary in both sky coverage and exposure time, reaching 29 000 s for fields with well-studied galaxies, down to ~100 s for the shallowest survey, which covers 63 per cent of the sky. For galaxies observed in multiple surveys, we chose the highest exposure-time image which contained the entire photometric aperture in the field-of-view. Although the PSF is distorted near the edge of the field (Morrissey et al. 2007), we found that this did not affect the photometry. The tilename for each galaxy identifies the exposure and is given in Table 1.

We similarly used ELLIPSE in IRAF to measure the GALEX images, although we estimated the sky differently. While the GALEX pipeline provides background images, we noticed galaxy flux in the background images for some objects. We therefore opted for traditional background estimation from an annulus. Unfortunately, FITSKY in IRAF does not perform well when the background counts are very small, as it expects sky values to be normally distributed. We therefore implemented the method described in Gil de Paz et al. (2007), which divides two elliptical annuli into radial segments and averages over those segments. Similar to Gil de Paz et al. (2007), we divided the annuli into 90 segments total, with a typical segment area of 4000 pixels. We set the semimajor axis of the inner annulus at 1.5 times the semimajor axis of the photometric aperture. The uncertainty of the background comes from the standard deviation of the segment mean values.

We tested our approach with 20 morphologically diverse galaxies from the Gil de Paz et al. (2007) atlas which overlapped our sample, and used the same D25 aperture. Despite using the same technique, we systematically measured less flux than Gil de Paz et al. (2007) by 0.1–0.4 mag. We did successfully reproduce the Gil de Paz et al. (2007) results with the original cutouts from the NASA/IPAC Extragalactic Database (NED), so we conclude that the discrepancy is due to changes in the GALEX pipeline. We also compare our measurements with Bai et al. (2015), who remeasured the Gil de Paz et al. (2007) atlas using data processed by the current GR6/7 pipeline. Our results agree with Bai et al. (2015) to an rms difference of 0.14 mag without a systematic trend in both the NUV and FUV bands, which we attribute to different background estimation methods. We conclude that our UV measurements are accurate and have an rms precision of 0.14 mag.

Our GALEX measurements are also in Table 2. They have not been corrected for extinction, although for all of our analysis we used the prescription in Gil de Paz et al. (2007) to apply extinction corrections to these measurements. Values for $E(B-V)$ are from the Schlegel, Finkbeiner & Davis (1998) maps obtained from the IRSA dust map service.

3.3 Separating dusty galaxies

Fig. 2 shows a colour-absolute magnitude diagram that illustrates the diversity in the shape of the SED for the ATLAS3D and Rampazzo et al. (2013) galaxies. The majority of ETGs are extremely deficient in UV photons, as is expected from their generally old stellar populations. There appears to be a trend in the SED, where more UV-rich galaxies tend to be less luminous. This trend appears unrelated to the MIR classes of Rampazzo et al. (2013), although the RSA Spitzer-IRS Atlas contains few low-luminosity ETGs. The region with blue ETGs is also sparsely populated compared to the area with NUV-W1 > 5. The Class-4 object which is an outlier at the bottom-right is NGC 1275, a Seyfert 1.5 galaxy in the Rampazzo et al. (2013) sample. There does not appear to be
foreground contamination for this galaxy, so we believe the extreme NUV-W1 colour and luminosity are due to the AGN component.

As indicated by Rampazzo et al. (2013), about half of ETGs contain observable traces of interstellar dust, which can dominate the MIR signal. We therefore attempted to separate the passive from the non-passive galaxies. For the Rampazzo et al. (2013) sample, non-passive galaxies are classified from Spitzer-IRS spectra as Class-1–4 fairly reliably. The ATLAS3D sample does not have MIR spectra, so we attempt to distinguish between passive and non-passive galaxies with the extensive ancillary data.

Martini et al. (2013) demonstrated a one-to-one correspondence between optical dust lanes observed with the Hubble Space Telescope (HST) and emission from cold dust detected by Spitzer MIPS. We attempted to remove obvious contaminants with observed dust features in r-band observations (Krajnović et al. 2011). However, since the photometric resolution of SDSS is significantly lower than HST, we also searched for false negatives in our sample by cross-matching the dust detections in Martini et al. (2013) to the non-detections in Krajnović et al. (2011). This revealed many cases where the ATLAS3D images did not reveal dust lanes that were clearly visible with HST and via FIR detections, so we also excluded galaxies with CO detections (Young et al. 2011). Fig. 3 shows the W1–W3 versus W1–W4 colours for galaxies without evidence for diffuse, interstellar dust. We also compare this sample to SPS tracks with metallicities that bracket the ATLAS3D sample. We used SPS models with an exponential SFH time-scale of 100 Myr. We also included a minimum sSFR of $10^{-14}$ yr$^{-1}$ to account for constant, very low levels of star formation (Ford & Bregman 2013). Fig. 3 shows that the Flexible Stellar Population Synthesis (FSPS) high and median metallicity model tracks follow the shape of the data quite well, albeit with an offset. We explore the source of this offset in Section 4.2.

When compared to the passive Class-0 galaxies from Rampazzo et al. (2013), there still appears to be a tail extending redward of the clump of Class-0 galaxies. The single Class-0 object in the tail is NGC 4377, which has potential foreground contamination. Therefore, we performed an external check on this sample by cross-matching with Herschel detections at FIR wavelengths (Smith et al. 2012; di Serego Alighieri et al. 2013; Amblard et al. 2014). For objects in Amblard et al. (2014) we defined a ‘dust detection’ as a 5σ detection in at least one of the 250, 350, and 500 μm bands. For galaxies from the other two studies, we used their internal criteria to indicate a dust detection. We note that two of the Class-0 objects had Herschel FIR detections, along with 31 per cent of the overlapping ATLAS3D sample, which suggests there is still substantial contamination. The regions of the colour–colour diagram not populated by the galaxies with FIR detections are W1 − W3 < 0.67 and W1 − W4 < 1.52 (AB: W1 − W3 < −1.85 and W1 − W4 < −2.40). NGC 4486A, a tidally disrupted satellite of M87, is the only galaxy in this region with a marginal Herschel detection at 250 μm. Because of its tidal interactions, we classify it as a peculiar case, and assume that the rest of the galaxies in this region do not contain interstellar dust. We denote the galaxies in this region as the ‘colour-cut dustless’ sample, compared to the subset with only CO and/or dust exclusions, which we just term ‘dustless’.

4 STELLAR POPULATION SYNTHESIS MODELS AND CIRCUMSTELLAR DUST

We used the GaLEX, 2MASS, and WISE photometry to construct broad-band SEDs for our sample. These SEDs are shown in Fig. 4, normalized to the K band. NGC 2974 is a very large outlier in W1 and W2, most likely due to very severe foreground contamination from a nearby bright star. While its photometry is reported in Table 2, we exclude it from our plots due to its suspect colour.

We compare our data to the FSPS v2.5 models (Conroy et al. 2009; Conroy & Gunn 2010), which recently incorporated
Figure 4. Spectral energy distributions of galaxies within the K20 aperture from broad-band FUV, NUV, J, H, Ks, W1, W2, W3, W4 photometry, normalized to the Ks band. Model spectra are high-metallicity FSPS models (Conroy, Gunn & White 2009; Conroy & Gunn 2010) with exponentially decreasing SFH with $t_{\text{SFH}} = 100$ Myr and $[Z/H] = 0.2$. The different spectra represent $t = 0.1, 1, 5$, and 10 Gyr ages. Data points are the combined ATLAS3D and Rampazzo et al. (2013) galaxies. ATLAS3D galaxies without CO detections and dust lane morphology, or Rampazzo et al. (2013) Class-0 galaxies make up the passive group, while those with either detection, or classified as Rampazzo et al. (2013) Class-1–4, are in the non-passive group.

circumstellar dust (Villaume et al. 2015). These models allow for very extensive customization of isochrones and stellar atmosphere libraries. The FSPS models match the data well, particularly in the UV. In W3 and W4 many of the points extend above the model predictions. However, in the dustless sample described in Section 3.3 fall well within the range of colours predicted by the models.

4.1 Stellar mass-to-light ratios

One valuable use for SPS models has been to predict stellar mass-to-light ratios ($M/L$) for galaxies from broad-band colours (Bell & de Jong 2001; Bell et al. 2003; Zibetti, Charlot & Rix 2009). Bell & de Jong (2001) illustrated the power of this approach with their relation between $M/L_B$ and $B - R$ colour, which was largely robust to metallicity, extinction, and bursty SFH. More recent improvements to $M/L$ determinations include the use of multiple colours and models of dust extinction (Zibetti et al. 2009). Yet despite these improvements, the presence of young stellar populations and internal extinction remains a major source of uncertainty for these models (Bell & de Jong 2001; MacArthur et al. 2004; Zibetti et al. 2009). These uncertainties are less severe at longer wavelengths, where the effects of young stellar populations and extinction on the $M/L$ ratio are diminished (Meidt et al. 2014). However, this reduction in uncertainty comes at a cost of increased uncertainties in modelling the AGB phase in the stellar models, which are especially poorly studied at low metallicity (Maraston et al. 2006). SPS models predict that the impact of AGB stars peak around 1 Gyr and decrease at greater ages (Melbourne et al. 2012), so should be less important for most ETGs.

Many different prescriptions exist to determine stellar masses of galaxies (e.g. Cluver et al. 2014; Meidt et al. 2014) that are either directly based on or calibrated from SPS models (Bruzual & Charlot 2003; Salim et al. 2007). However, the accuracy of these prescriptions is limited by the uncertainties associated with models for evolved stars, the dust geometry, Initial Mass Function (IMF), and SFH.

Stellar mass-to-light ratios determined by dynamical means from ATLAS3D are extremely valuable because they are not dependent on the same assumptions made by SPS models, such as an IMF. Results from ATLAS3D indicate a tension between stellar masses generated from SPS models and from dynamics, which is correlated with observed velocity dispersions. This disagreement has been put forward as evidence that the IMF may be variable (Cappellari et al. 2012; van Dokkum & Conroy 2012), which would imply greater and systematic uncertainties in SPS-derived stellar masses that assume a universal IMF.

In order to determine if the tension is also seen in the MIR, we transformed the ATLAS3D mass-to-light ratio from $r$ band to W1, and corrected for the difference between the largest Multi-Gaussian Expansion (MGE) aperture used in ATLAS3D and the modified K20 aperture used here. The band was transformed according to the formula:

$$
\log_{10} \left( \frac{M}{L_{W1}} \right)_{\text{K20}} = \log_{10} \left( \frac{M}{L_r} \right)_{\text{MGE}} + \log_{10} \left( \frac{L_r}{L_\odot} \right) + 0.4 \left( m_{W1,\odot} - 5 \log_{10} \left( \frac{d}{10 \text{ pc}} \right) - M_{W1,\odot} \right),
$$

where $(M/L_{W1})_{\text{K20}}$ is the mass-to-light ratio within the K20 aperture in W1, $(M/L_r)_{\text{MGE}}$ is the ATLAS3D mass-to-light ratio within the region where the surface brightness is accurately modelled by the MGE, $L_r/L_\odot$ is the $r$-band luminosity of the galaxy in units of the in-band solar luminosity with $M_{\odot} = 4.64$ in AB magnitudes (Blanton & Roweis 2007), $m_{W1}$ is the AB magnitude of the galaxy as measured in this work, $d$ is the distance to the galaxy, and $M_{W1,\odot} = 5.94$ mag is the absolute magnitude of the Sun in AB magnitudes (transformed from the Vega value in Jarrett et al. 2013). This transformation assumes that the stellar mass-to-light ratio is spatially constant, which is consistent with assumptions made in JAM modelling (Cappellari et al. 2013). In order to find an aperture representative of the total flux of the galaxy measured by ATLAS3D, we numerically integrated the MGE intensity model in an elliptical aperture such that at least 90 per cent of the flux would be in that aperture. This cut-off was chosen because the accuracy of the integrated flux of the MGE models compared to SDSS fluxes is 10 per cent (Scott et al. 2013). The transformed mass-to-light ratios are shown in Fig. 5. The uncertainty of the mass-to-light ratio for each data point includes the photometric and zero-point uncertainties in $W1$, the photometric uncertainty in $r$ band (Scott et al. 2013), JAM modelling uncertainties (Cappellari et al. 2013), and distance uncertainties (Cappellari et al. 2011).

Although extinction is greatly reduced in the MIR, non-stellar emission – dust in particular – can be a major contaminant, introducing uncertainties of up to 30 per cent when integrated over the entire galaxy (Meidt et al. 2012). We therefore use the colour-cut dustless sample, described in Section 3.3, to minimize interstellar dust contamination.

The colour-cut dustless galaxies in Fig. 5 do not appear affected by diffuse, interstellar dust, nor is there a noticeable trend in W1–W2. We calculate that $\log_{10}(M/L_{W1}) = 0.07 \pm 0.13$ for old stellar populations without diffuse dust. This value contrasts with the result of Meidt et al. (2014) of $\log_{10}(M/L_{W1}) = 0.25 \pm 0.11$. The offset is consistent with the IMF transition from Chabrier (2003) to Salpeter (1955) with increasing velocity dispersion found by Cappellari et al. (2012) and van Dokkum & Conroy (2012). To
Stellar mass-to-light in the W1 band for the ATLAS3D sample along with several SPS predictions and empirical measurements. The data points are converted from the ATLAS3D p-band stellar mass-to-light ratio, corrected to match the 2MASS K20 aperture. Large blue points meet the colour-cut dustless criteria defined in Section 3.3, while small grey points do not. A representative error bar is given in the lower left. The red line is the relation of Cluver et al. (2014) from the GAMA survey. The green solid and dashed lines indicate the M/L versus W1–W2 relation and dispersion from Meidt et al. (2014) for old, stellar populations, derived from the Bruzual & Charlot (2003) models. The horizontal dotted green line represents the colour-independent M/L suggested by Meidt et al. (2014) using an age–metallicity relation for ETGs. The dashed and dotted lines connect square points from FSPS models with Salpeter (1955) and Chabrier (2003) IMFs, respectively, evaluated at three different metallicities (from left to right): [Z/H] = −0.89, 0.0, 0.20 for a 10 Gyr population. Closed squares use W1–W2 directly from FSPS. Open squares use W1–W2 colours as corrected by Meidt et al. (2014).

We also compare our results to an empirically derived M/L versus W1–W2 relation (Meidt et al. 2014) relation was fit to the resolved portion of the GAMA sample, with stellar masses derived from optical colours (Taylor et al. 2011). This difference in how the fits are popularly leads to the difference in the slope. Secondly, the Meidt et al. (2014) relation was fit to a pure stellar population, while the Cluver et al. (2014) relation was fit to very dusty galaxies. This likely explains why the relation seems to trace the dusty population, but is very discrepant with the dust-free ETGs.

4.2 Evidence for ubiquitous circumstellar dust

All low- to intermediate-mass stars (between 0.5 and 8 M☉) pass through the AGB when undergoing hydrogen and helium shell burning (Marigo et al. 2008). These stars have extremely cool and tenuous atmospheres where dust grains condense and drive mass loss (Salpeter 1974a,b; Goldreich & Scoville 1976; Bedijn 1987). As a result, we expect to observe this stage of stellar evolution in populations with ages ranging from 100 Myr to greater than the age of the Universe. However, SSP models indicate that the effects of circumstellar dust on integrated MIR flux peaks at 1 Gyr after star formation, and then decreases significantly by 10 Gyr (Villaume et al. 2015).

Circumstellar dust emission has been proposed as an age tracer of old stellar populations because broad-band optical colours have an age–metallicity degeneracy (Bressan et al. 1998). Despite the lack of specific MIR age indicators for theWISE bands, SPS modelling can potentially yield an evolutionary track for a given colour due to circumstellar dust (Villaume et al. 2015). Bregman, Temi & Bregman (2006) showed that there is some tension between ages determined from optical line indices and circumstellar dust fits. We compare these two age determinations for the ATLAS3D sample using the FSPS models. We also investigate the effect of circumstellar dust on SFR indicators in the MIR for galaxies with low specific SFRs (sSFR = SFR/M*).

We used MIR colours to obtain a distance-independent measurement of circumstellar dust. Flux in the short-wavelength W1 and W2 bands is largely dominated by the stellar continuum and is not sensitive to dust (e.g. Villaume et al. 2015). In contrast, the longer wavelength W3 and W4 bands should be increasingly sensitive to dust, since they lie in the region of the spectrum where circumstellar dust emission dominates over photospheric emission. We avoid the W2 band in comparing data to models because the effect of CO absorption alluded to in Section 4.1 has not been included in all SPS models (Peletier et al. 2012; Norris et al. 2014).

It is apparent from Fig. 3 that circumstellar dust is necessary in order to explain MIR colours; however, there is an offset between the tracks and the data. We explore the source of this offset in more detail in Figs 6 and 7. In Fig. 6 we used SSP ages for the ATLAS3D sample from McDermid et al. (2015) derived by fitting optical line indices. Since the SSP ages in McDermid et al. (2015) were not constrained to be consistent with the age of the Universe, we set the galaxies with SSP ages greater than 14 Gyr to have ages of 14 Gyr, in order to be consistent with current cosmological models (Planck Collaboration 2014); this was 19 per cent of the sample. While the discrepancies in W1–W3 do not seem to be too large, the models appear to underpredict the flux in W4 by a factor of 2.5, which is comparable to the offset seen in Fig. 3. As seen in Fig. 7, mass-weighted ages estimate galaxies to be older, making the offset even more apparent. The potential causes of this discrepancy could include a ubiquitous intermediate-age population whose influence is seen in the MIR, but not detectable in the optical, and that a wider
mass range of AGB stars produce circumstellar dust at subsolar metallicities than predicted by the models.

Fig. 7 compares the FSPS models to the PARSEC v1.2S + COLIBRI PR16 SSP models (Bressan et al. 2012; Marigo et al. 2013; Rosenfeld et al. 2016) and the Marigo et al. (2008) models. The PARSEC models seem to predict no circumstellar dust at late ages, exacerbating the tension seen with the FSPS models. On the other hand, the Marigo et al. (2008) models predict more dust at late times compared to both the FSPS and PARSEC models. However, the predicted colours of the dusty stellar population are still bluer than indicated by the data.

While some of the extremely red galaxies are likely contaminated by interstellar dust, it is significant that very few galaxies are consistent with having no circumstellar dust. Since the number of galaxies redder than the no-circumstellar-dust models is significantly greater than our estimated contamination rate, we conclude that circumstellar dust is the source of the MIR excess for galaxies without interstellar dust. These results are robust to differences in the IMF.

4.3 Impact of circumstellar dust on MIR SFRs

Accurate SFRs provide valuable insights into galaxy formation. The most direct method to determine SFR measures Balmer emission from H II regions, which is related to the number of ionizing photons from young stars; however, the extinction corrections can be substantial and uncertain (Kennicutt 1998b). SFRs derived from MIR to FIR observations are more indirect as they measure the SFR through radiation reprocessed by dust grains. This method is quite insensitive to extinction uncertainties, but at low SFRs the old stellar population may also significantly heat the dust (Helou 1986; Lonsdale Persson & Helou 1987; Kennicutt 1998a; Groves et al. 2012).

We quantify the important contribution of circumstellar dust to the total MIR luminosity, and its impact on SFR estimates with WISE W1, W3, and W4. W1 traces the old stellar population that dominates stellar mass, and W3 and W4 trace the PAHs and warm dust heated by young stars, respectively, so sSFR can be calculated without additional observations. Although W4 is considered a superior tracer of SFR over W3, fainter galaxies are more readily detected in W3. Since SFRs can be measured in W3 for galaxies too faint for a W4 detection, we include it in our analysis of SFR measurements.

Davis et al. (2014) investigated the impact of circumstellar dust on SFR for the ATLAS3D sample using WISE catalogue photometry, with prescriptions calibrated for Spitzer bands. We reinvestigate this prescription with our updated photometry, more stringent criteria for dustless galaxies, and with the more recent SFR relations of Cluver et al. (2014).

We plot the W1 versus W3 and W4 luminosity for the ATLAS3D sample in Fig. 8 (see fig. 1 of Davis et al. 2014 for a similar plot with K_s). The colour-cut dustless sample described in Section 3.3 is
shown in red. The colour-cut sample was chosen because it should have less interstellar dust contamination compared to the regular dustless sample, and should represent an accurate relation between W1 and W3 (or W4) in the absence of star formation. Because we may have excluded some truly dust-free galaxies whose colours do not match our exclusion criteria, the scatter in our relation may be underestimated. Follow-up observations of the ATLAS$^3$D sample with FIR/submillimetre measurements or high-resolution visible-wavelength images to search for dust lanes would result in a more representative sample of dustless galaxies.

In order to characterize the minimum SFR which can be usefully measured with W4 observations, we calculate sSFR limits with the relations in Cluver et al. (2014) and use the mean W1–W2 value of our sample to get $M/L_{W1}$. The results shown in Fig. 8 indicate that the contribution of circumstellar dust to W3 and W4 will mimic an sSFR of $2 \times 10^{-12}$ yr$^{-1}$. Lower values of sSFR cannot be reliably inferred with integrated WISE photometry alone.

Even at larger sSFR values, it is still necessary to remove the effect of circumstellar dust. In order to quantify the effect, we fit a line to the dustless detections and obtain

$$\log \nu L_{W3} = 1.03 \log L_{W1} + 30.58,$$

$$\log \nu L_{W4} = 0.97 \log L_{W1} + 30.72$$

with an rms scatter of 0.03 and 0.04 dex, where $L_{W1}$ is the ‘in-band’ luminosity in solar luminosities, and $\nu L_{\nu}$ is the spectral luminosity of the band in erg s$^{-1}$. These relations may be used to subtract the circumstellar dust contribution to W3 or W4 for relatively quiescent galaxies. The W4 relation is similar to the relation derived by Davis et al. (2014) between $K_{S}$ and W4. These corrections will likely be negligible for typical star-forming galaxies as the sSFR of local $L^*$ galaxies is around $10^{-10}$ yr$^{-1}$ (Cluver et al. 2014).

5 PAH RATIOS WITH GALEX AND WISE

MIR spectra of ETGs have shown that many exhibit much weaker short-wavelength PAH features (6.2, 7.7, and 8.6 $\mu$m) relative to those at longer wavelengths (e.g. 11.3 and 12.7 $\mu$m; Kenada et al. 2005, 2008; Vega et al. 2010; Rampazzo et al. 2013) compared to star-forming galaxies (Helou et al. 2000; Brandl et al. 2004; Smith et al. 2007). Observations of later-type galaxies have also shown that low values of these band ratios are commonly found in low-luminosity AGN (Smith et al. 2007; O’Dowd et al. 2009). Many ETGs contain evidence for LINERs (Ho, Filippenko & Sargent 1997), although as most may not be dominated by AGN (Sarzi et al. 2010), it is not clear if there is a direct connection between AGN and the proportionally weaker short-wavelength PAH bands in ETGs.

5.1 Environments of anomalous PAH ratios

We have used data from three significant studies of PAH emission from nearby galaxies to probe the relationship between PAH emission, AGN, and host galaxy morphology to further explore the different PAH band ratios seen in ETGs. The largest study of ETGs is the IRS Spitzer-IRS Atlas by Rampazzo et al. (2013), and about half of their sample of ETGs exhibit PAH emission. Smith et al. (2007) performed a detailed analysis of PAH emission from galaxies in the Spitzer Infrared Nearby Galaxy Survey (SINGS; Kennicutt et al. 2003). This sample spans a wide range of luminosity and infrared to visible wavelength flux ratio, and includes early- and late-type galaxies. They have also classified the galaxies as either ‘H ii’ galaxies, which are dominated by star formation, LINERs, or Seyferts. Finally, Diamond-Stanic & Rieke (2010) studied 35 Seyfert galaxies in the RSA catalogue. All of these Seyferts have late-type host galaxies (later than SO), and generally exhibit weaker short-wavelength PAH emission compared to H ii galaxies. This study included 21 galaxies with PAH emission in spectra not centred on the nuclear region, and these off-nuclear spectra exhibit PAH ratios similar to H ii galaxies.

Diamond-Stanic & Rieke (2010) investigated if the weaker 6.2, 7.7, and 8.6 $\mu$m bands in Seyferts could be due to radiative or mechanical processing. Previous work (DeFrees et al. 1993; Szczepanski & Vala 1993; Hudgins & Allamandola 1995; Langhoff 1996) has shown that the C–C stretching modes that give rise to the 6.2 and 7.7 $\mu$m features, and the C–H in-plane bending modes that give rise to the 8.6 $\mu$m feature, are more readily produced in ionized PAHs. The ratio of these features to the C–H out-of-plane bending mode that gives rise to the 11.3 $\mu$m feature (Duley & Williams 1981; Allamandola, Tieless & Barker 1989) will be lower for more neutral PAHs. Fig. 9 shows the ratio of 11.3 $\mu$m/7.7 $\mu$m versus 6.2 $\mu$m/7.7 $\mu$m for measurements from these three studies. The ETGs include both the Rampazzo et al. (2013) sample and ETGs in Smith et al. (2007), the Seyfert sample includes late-type Seyferts from both Smith et al. (2007) and Diamond-Stanic & Rieke (2010), and the LINERs and H ii galaxies are only galaxies with late-type morphology from Smith et al. (2007). This diagram clearly shows that the ETGs have larger 11.3 $\mu$m/7.7 $\mu$m than the H ii galaxies, but also that the ratio is larger than for the Seyferts and perhaps the LINER sample. Only galaxies with detections in both ratios are shown, as the literature sources generally do not quote upper limits for non-detections. Very different values of 11.3 $\mu$m/7.7 $\mu$m versus 6.2 $\mu$m/7.7 $\mu$m are expected for neutral versus ionized PAHs. Allamandola, Hudgins & Sandford (1999) and Draine & Li (2001) showed that neutral PAHs lead to the intensity ratio 11.3 $\mu$m/7.7 $\mu$m $> 0.4$, whereas 11.3 $\mu$m/7.7 $\mu$m $< 0.2$ is more
characteristic of ionized PAHs, although the value of this ratio also depends on the PAH size distribution, as does the 6.2 μm/7.7 μm ratio. Only about half of the ETGs have 11.3 μm/7.7 μm > 0.4 as expected for neutral PAHs.

Fig. 10 plots the cumulative distribution functions of these four classes of galaxies. We used a Kolmogorov–Smirnov two-sample test to measure the significance of the differences. We found that the 7.7 μm/11.3 μm difference between the ETGs and the Seyferts, as well as between the ETGs and the H II galaxies, is very significant (p ≪ 0.01). The difference between the ETGs and LINERS is marginally significant (p ~ 0.02) as well. Note that the LINER sample is somewhat smaller than the other samples, and that the cumulative distributions contain all galaxies with detections in the single ratio, and thus may have more points than Fig. 9.

Galliano et al. (2008) noted that the typical ionization state of PAHs is set by $G_0 T^{1/2}/n_e$ (Bakes & Tielens 1994), where $G_0$ is the intensity of the UV radiation field, $T$ is the gas temperature, and $n_e$ is the electron density, and we investigated if the distribution of Class-2 and Class-3 objects followed trends in any of these physical quantities. The gas temperature can be determined from the $H_2 S(3)/H_2 S(1)$ line ratio, and the electron density can be determined from $[S III] 18.7 \mu m/[S III] 33.5 \mu m$. These lines have been measured by Rampazzo et al. (2013), and any trends should cause the two classes to separate in one of the dimensions. As seen in Fig. 11, Class-2 and Class-3 objects have similar values of these ratios, so
we conclude that trends with gas temperature or electron density are not the origin of the difference between the two classes.

Since the temperatures and densities for the Class-2 and Class-3 galaxies are similar, we expect the degree of ionization for PAHs will depend on the shape of the interstellar radiation field (ISRF; Weingartner & Draine 2001). The ISRF in early- and late-type galaxies varies dramatically, both in normalization and shape. The dramatic lack of young stars, and therefore UV emission, can even lead optical photons to become the primary heating mechanism for interstellar dust (Groves et al. 2012). While we do not directly measure the intensity of the ISRF, we use the NUV – J colour as a proxy for the slope. We show the trend in the slope of the radiation field with the 7.7 µm/11.3 µm ratio in Fig. 12. Even though Class-4 objects also have PAH emission, they were excluded as likely AGN because their high 1.4 GHz and nuclear X-ray emission may distort the ISRF (Rampazzo et al. 2013). There does not appear to be any correlation between the shape of the ISRF and the 7.7 µm/11.3 µm ratio, which corresponds directly with MIR class.

While the relation between ionization state and UV intensity works well for many environments (Joblin et al. 1996; Bregman & Temi 2005), Diamond-Stanic & Rieke (2010) pointed out that many Seyferts have ratios consistent with completely neutral PAHs, or even more extreme ratios than the models allow, and in any case the more intense radiation field associated with AGN should not lead to less ionization. We find that the ETGs often have even smaller values of the 7.7 µm/11.3 µm band ratio than the Seyferts. Draine & Li (2001) noted that smaller values of 7.7 µm/11.3 µm could be produced in the charging conditions characteristic of the cold neutral medium (CNM) or warm ionized medium (WIM), which have lower densities and radiation field intensities than typical of the photodissociation regions (PDRs) associated with star formation. If most of the PAHs are associated with conditions more similar to the CNM or WIM, this could explain the dramatic difference in their ratios relative to star-forming galaxies, as well as why they are not similar to Seyferts, which typically also have PDRs.

As the three shorter wavelength PAH features are also associated with smaller PAHs, an alternative explanation of their proportionally lower fluxes is a different size distribution (Schutte, Tielens & Allamandola 1993; Draine & Li 2001; Galliano et al. 2008). Experimental work on PAHs has indicated that PAHs below 15–20 C atoms would be destroyed in most environments, PAHs smaller than 20–30 C atoms may be stripped of their H atoms, and PAHs of 30–50 C atoms would mostly be photoionized (Jochims et al. 1994; Allain, Leach & Sedlmayr 1996). If smaller PAHs have been destroyed, then this would also lead to lower 6.2 µm relative to 7.7 µm and lower 7.7 µm relative to 8.6 µm. Fig. 13 shows these two ratios for the same galaxies shown in Fig. 9. Based on inspection of this figure, as well as Kolmogorov–Smirnov (KS) tests applied to the cumulative distributions, we do not see significant differences between the ETGs and other populations. Diamond-Stanic & Rieke (2010) similarly did not find significant differences between Seyferts and either their off-nuclear positions or the H ii galaxies from Smith et al. (2007). As illustrated in Draine & Li (2001), larger PAHs can...
Figure 14. Left: relative strength of the $\text{H}_2(3)$ transition to PAH emission, which traces shocks in cold gas, versus the 7.7 μm/11.3 μm ratio. Black points are ETGs from Rampazzo et al. (2013) while blue points are Seyferts from Diamond-Stanic & Rieke (2010). Stars indicate Class-4 galaxies. Both the ETGs and Seyferts indicate a correlation between the shocks and anomalous PAH ratios. Right: molecular hydrogen strength versus nuclear X-ray luminosity for Rampazzo et al. (2013) galaxies with nuclear X-ray detections. As noted in Diamond-Stanic & Rieke (2010), there does not appear to be a trend between shock strength and X-ray luminosity.

also contribute to the larger 11.3 μm/7.7 μm ratios seen in Fig. 9, although they also have smaller 6.2 μm/7.7 μm ratios. Intriguingly, about half of the ETGs have 6.2 μm/7.7 μm < 0.25, although the difference is not formally significant. Careful estimates of upper limits on the weak 6.2 μm feature in the several ETGs with only 7.7 μm detections, as well as more sensitive measurements with future facilities, would help to better characterize the smaller PAHs in these galaxies that are most sensitive to destruction processes.

Another explanation proposed for the variations in 7.7 μm/11.3 μm is interstellar shocks. Shock velocities of on order 100 km s$^{-1}$ can reduce the relative number of small grains (Jones et al. 1994; Micelotta, Jones & Tielens 2010), and thus lead to weaker emission in all three of the shorter wavelength features. If shocks are present, then the galaxies may also exhibit strong $\text{H}_2$ emission. Many studies have found a correlation between $\text{H}_2$ emission and the 7.7 μm/11.3 μm ratio (Ogle et al. 2007; Roussel et al. 2007; Kaneda et al. 2008; Vega et al. 2010). Fig. 14 (left) illustrates the correlation shown by Diamond-Stanic & Rieke (2010) for the RSA Seyferts, along with the ETGs from Rampazzo et al. (2013). The ETGs mostly follow the same trend as the Seyferts, although they generally have more $\text{H}_2$ emission and there is more dispersion in 7.7 μm/11.3 μm for the ETGs with the proportionally strongest $\text{H}_2$ emission. Diamond-Stanic & Rieke (2010) and Rampazzo et al. (2013) found that AGN power did not correlate with this ratio, and Fig. 14 (right) confirms this point with a plot of the ratio of $\text{H}_2$S(3)/(7.7 μm + 11.3 μm) versus nuclear X-ray luminosity from Pellegrini (2010). Processing by shocks appears to be a more viable contributor to the 7.7 μm/11.3 μm ratios in ETGs, as it is for Seyferts.

In addition to the preferential destruction of small PAHs, shocks could also affect the chemistry of the PAHs, even those that are fully hydrogenated. For example, the 11.3 μm band is produced by single C–H bonds, while the 12.7 μm feature is produced by C–H multiplets (Hony et al. 2001). Diamond-Stanic & Rieke (2010) found that Seyferts exhibit significantly smaller ratios of 12.7 μm/11.3 μm than off-nuclear and $\text{H}_\beta$ galaxies, which could be due to different processing. Figs 15 and 10 show that the ETGs are not significantly different from the Seyferts or the $\text{H}_\beta$ galaxies, so we see no evidence that this is an important physical difference in the ETG population. The 12.7 μm/11.3 μm band ratio shown in Fig. 15 is plotted versus the 17 μm/11.3 μm band ratio. Both the 11.3 μm band and the 17 μm band originate from neutral PAHs, and so their relative strength is primarily sensitive to the size distribution. Smith et al. (2007) found that the larger 17 μm/11.3 μm intensity ratio...
correlates with metallicity, and suggest that it may be easier to form the larger grains that contribute to the 17 μm band in higher metallicity environments. They find that 17 μm/11.3 μm is largest in Seyferts and suggest that these high ratios are due to a combination of the higher metallicities of the Seyfert hosts and the relative destruction of the carriers of the shorter wavelength 11.3 μm feature. As shown in Fig. 15, we find that ETGs have significantly lower 17 μm/11.3 μm ratios than the Seyferts (KS p < 0.0001) and LINERs (KS p < 0.0001) from Smith et al. (2007), and are similar to H II galaxies (see also Fig. 10). Early-type galaxies may have lower 17 μm/11.3 μm band ratios because they lack the hard radiation field of Seyferts. Alternatively, this ratio could be lower in some ETGs because their PAHs have been externally accreted from lower metallicity dwarf galaxies.

We cannot separate the effect of metallicity on the 17 μm/11.3 μm ratio because of the sparse overlap between the ATLAS³D and Rampazzo et al. (2013) samples. Only 13 galaxies in our sample have both ATLAS³D metallicity and 17 μm/11.3 μm measurements; their Pearson correlation coefficient is −0.04, which indicates a very weak anticorrelation.

### 5.2 Photometric PAH classification

Currently the only way to discriminate between MIR classes is through infrared spectra from targeted spectroscopic observations in space. This is a significant investment for space-based missions which are already highly oversubscribed. Now that the WISE mission has imaged the entire sky in the MIR, a successful method of classification has imaging the carriers of the shorter wavelength 11 μm feature. The only band sensitive to PAH emission is W3, which covers all of the 7.7, 8.6, 11.3, and 12.7 μm PAH complexes (Wright et al. 2010). The W3 band accomplishes this amount of spectral coverage with a wide effective bandwidth of 5.5 μm (Jarrett et al. 2001). By comparison, the typical equivalent width of a line is around 0.1 μm (Rampazzo et al. 2013). Therefore, the

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**Figure 16.** Left: W1–W2 versus W2–W3 for the sample of galaxies in Rampazzo et al. (2013). W1–W2 is sensitive to the stellar population, so we do not see separation based on properties of the interstellar dust. W2–W3 measures the presence of PAH features compared to the stellar population. This causes the Class-0 objects separate from the Class-2–4 objects. Galaxies located off the plot are IC 5063, NGC 1052, NGC 1275, NGC 2685, NGC 4383, and NGC 5128. Right: W2–W3 versus W3–W4 for the sample of galaxies in Rampazzo et al. (2013). There does not appear to be strong discrimination in W3–W4 due to the hot dust population, as seen in W2–W3. Located off the plot to the top and to the right are all Class-4 objects, NGC 2685, NGC 3245, NGC 4383, and NGC 4435.

**Figure 17.** Cumulative histogram of the W2–W3 colours of the Class-0, Class-2, and Class-3 objects. The Class-0 objects are from a population statistically distinct from both the Class-2 and Class-3 objects. We propose a colour-cut to distinguish between Class-0 and Class-2–3 objects at W2 – W3 = −1.2 (AB), which is denoted by the red dashed line. Class-4 objects are from a population statistically distinct from all other classes. There are no other separations which can be made using W2–W3 colours.

both classes in W2–W3 is shown in Fig. 17. 85 per cent of Class-0, 11 per cent of Class-2, and no Class-3 objects are bluer than W2 – W3 = 0.635 (Vega, or −1.2 AB), providing a convenient colour-cut between dusty and passive ETGs. No other major distinctions between classes are statistically significant.

One reason why WISE is unable to discriminate between classes very well is because the bands are not well placed with respect to PAH features. The only band sensitive to PAH emission is W3, which covers all of the 7.7, 8.6, 11.3, and 12.7 μm PAH complexes (Wright et al. 2010). The W3 band accomplishes this amount of spectral coverage with a wide effective bandwidth of 5.5 μm (Jarrett et al. 2011). By comparison, the typical equivalent width of a line is around 0.1 μm (Rampazzo et al. 2013). Therefore, the
difference between the presence and absence of all five PAH lines is around 0.1 mag, which is similar to the photometric error of our measurements. While this should suffice to separate Class-0 objects from Class-2/3 objects, separation of Class-2 and Class-3 objects requires more precise photometry. Another complication is the large intrinsic scatter in Class-2 and Class-3, which we attribute to varying levels of contribution by the dust continuum.

Despite the fact that WISE colours on their own cannot discriminate between the MIR classes, they can be useful for informing follow-up targets. This will be particularly true with the Mid-Infrared Instrument (MIRI) on the James Webb Space Telescope (JWST). For galaxies which have W2–W3 colours consistent with some interstellar dust, better demographics on the prevalence of anomalous PAH ratios can be determined from follow-up with the MIRI Medium Resolution Spectrograph (MRS).

6 CONCLUSIONS

We performed WISE and GALEX aperture photometry on a combined sample of 91 ETGs from Rampazzo et al. (2013) which had uniform MIR line flux measurements, and 260 ETGs from the ATLAST survey, which have significant ancillary data. The photometric accuracy is about 0.05 mag in the MIR and 0.1 mag in the UV. We chose an identical aperture to one used by the 2MASS XSC.

The MIR is a useful wavelength region to calculate stellar masses since the effects of extinction and young stars are reduced compared to shorter wavelengths. We converted the ATLAST (M/L)band from r band to W1 and corrected for the change in aperture between the two studies. We found that the ATLAST M/LW1 measurements are significantly larger than those predicted by SPS models. We did not find a trend between M/LW1 and W1–W2 for old stellar populations predicted by SPS models. We obtained an average log M/LW1 = 0.07 ± 0.13, which is based on dynamical M/LW1 rather than fits to SPS models. Our colour selection of dustless galaxies biases our value towards higher M/LW1; but without the colour-cut, we still observe a 2σ discrepancy.

Our high M/LW1 compared to SPS models agrees with recent research indicating that the IMF varies, and is more Salpeter like at high velocity dispersions. When the M/LW1 from our galaxies is compared to FSPS models with Chabrier (2003) and Salpeter (1955) IMFs, and we find that the dynamically derived masses mostly fall in-between the two IMFs, mirroring the effect seen from M/LW1 derived from optical spectra.

We clearly identify circumstellar dust in the W3 and W4 bands for many ETGs. Surprisingly, this circumstellar dust emission appears to be ubiquitous at much greater ages than predicted by SPS models, even after accounting for potential contamination in our dustless sample. We also find that W4 emission is underpredicted by models by about a factor of 2.5. This underprediction is also seen in other SPS models.

With all-sky coverage, the WISE mission makes stellar mass and SFR estimates very accessible. The WISE W3 and W4 bands are sensitive to dust warmed by recent star formation. For objects with low sSFR, circumstellar dust emission can contaminate these tracers, leading to an inflated result. We determined that circumstellar dust contributes approximately 2 × 10^{-11} yr^{-1} to the sSFR signal in both W3 and W4 and we provide relations to correct for the circumstellar dust contribution to W3 and W4.

Lastly, we compared MIR spectra for spirals, LINERS, Seyferts, and ETGs in order to investigate the source of anomalous PAH ratios. We found that ETGs and Seyferts have significantly distinct 7.7 μm/11.3 μm ratios from spirals, as well as from each other. This strongly suggested that the cause of anomalous PAH ratios is more than just the presence of an AGN. The ETGs also have significantly distinct 17 μm/11.3 μm values from the LINERS and Seyferts.

Using available [S ii] 18.7 μm/[S ii] 33.5 μm and H2S(3)/H2S(1) ratios, we noted that gas temperature and electron density do not correlate with the presence of anomalous PAH ratios. The incident UV flux on the PAHs also does not appear to correlate with 7.7 μm/11.3 μm ratio. Based on these results, we conclude that the anomalous PAH ratios are unlikely to be due to global variation in the ISRF.

We did not see evidence for the preferential destruction of smaller PAHs based on the 6.2 μm/7.7 μm and 8.6 μm/7.7 μm ratios. However, due to the non-uniform availability of upper limits in published line intensities, we excluded galaxies without detections. A uniform treatment of upper limits may reveal more information about small PAHs in these galaxies. We did not find evidence of dehydrogenation of small PAHs in the 12.7 μm/11.3 μm ratio.

The strongest correlation with anomalous PAH emission is the strength of shocks in H2. We found that both ETGs and Seyferts follow this trend, although ETGs generally have more H2 emission. Exactly how shocks bring about the anomalous emission is still largely uncertain. However, we determined from X-ray luminosities that it is likely unrelated to the activity of the central supermassive black hole.

One particularly interesting result we found was that the ETGs have 17 μm/11.3 μm ratios significantly lower than Seyferts and LINERS, but similar to spirals. This ratio is sensitive to the presence of large grains, and has been observed to trend with metallicity. Our result can be explained by the lack of the hard radiation environment found in Seyferts, or if the PAHs were accreted from an external, low-metallicity galaxy.

Finally, we attempted to use WISE to classify the PAH properties of ETGs. We found that WISE colours are only able to determine the presence of dust in ETGs, but not the MIR class. We conclude that finer distinctions are not possible because of the spectral placement of the WISE filters and our photometric precision. However, the W2–W3 colours may be able to inform detailed follow-up spectra of ETGs in order to more efficiently calculate the prevalence of anomalous PAH ratios.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 1. Aperture photometry parameters for galaxies in the ATLAS3D and Rampazzo et al. (2013) samples.

Table 2. Galaxy magnitudes for the ATLAS3D and Rampazzo et al. (2013) samples.

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