Modelling dust rings in early-type galaxies through a sequence of radiative transfer simulations and 2D image fitting

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ABSTRACT
A large fraction of early-type galaxies (ETGs) host prominent dust features, and central dust rings are arguably the most interesting among them. We present here ‘Lord Of The Rings’ (LOTR), a new methodology which allows to integrate the extinction by dust rings in a 2D fitting modelling of the surface brightness distribution. Our pipeline acts in two steps, first using the surface fitting software \textsc{Galfit} to determine the unabsorbed stellar emission, and then adopting the radiative transfer code \textsc{Skirt} to apply dust extinction. We apply our technique to NGC 4552 and NGC 4494, two nearby ETGs. We show that the extinction by a dust ring can mimic, in a surface brightness profile, a central point source (e.g. an unresolved nuclear stellar cluster or an active galactic nucleus; AGN) superimposed to a ‘core’ (i.e. a central flattening of the stellar light commonly observed in massive ETGs). We discuss how properly accounting for dust features is of paramount importance to derive correct fluxes especially for low luminosity AGNs (LLAGNs). We suggest that the geometries of dust features are strictly connected with how relaxed is the gravitational potential, i.e. with the evolutionary stage of the host galaxy. Additionally, we find hints that the dust mass contained in the ring relates to the AGN activity.

Key words: galaxies: structure — galaxies: individual: NGC 4552 (M 89, UGC 7760, VCC 1632), NGC 4494 (UGC 7662) — galaxies: evolution — galaxies: nuclei — galaxies: intergalactic medium

1 INTRODUCTION

Early-type galaxies (ETGs) are long known to host dust features of different nature, ranging from extended lanes crossing the whole galaxy, to inner disk or ring structures (e.g. Rest et al. 2001; Lauer et al. 2005). These peculiarities are usually overlooked in the analysis aimed at performing surface brightness fitting of the galaxy surface brightness distribution, due to the complexity of including a parametric model accounting for dust extinction. Hence, the approach used in arguably all studies is to mask the dust-affected area and exclude the corresponding data points from the fit.

Although sometimes unavoidable, this procedure is at least controversial, since the range of data exclusion is arbitrary, and can therefore unpredictably affect the choice of best-fit model. The most questionable situations are those involving the presence of a central dust ring/disk. The absorption produced by these features can in fact be indistinguishable from a real galaxy “core”, i.e. an intrinsic light deficit due to a lack of stars, common in massive galaxies ($M_B < -20.5$ mag; e.g. Kormendy et al. 2009; Graham 2016). All the studies regarding the central surface brightness of ETGs to date have preferentially excluded problematic, dusty objects from their analysis. However, in several cases, surface brightness fits have been attempted even in the presence of obvious obscuration (after heavy masking), and conclusions were drawn over the core/core-less nature of the objects (e.g. Lauer et al. 2007; Ferrarese et al. 2006; Richings, Uttley, & Körding 2011; Dullo & Graham 2014).

On top of this issue, an additional complication regards the potential presence of a central active galactic nucleus (AGN), and in particular of low-luminosity AGNs (LLAGNs). In fact, these objects posses an intrinsically low luminosity ($L_{bol} < 10^{42}$ erg/sec, $L_{bol} \sim 30 \times L_X$; e.g. Ho 2008), and hence they are easily over-shined by the high central intensity of core-less galaxies with large Sérsic in-
core hosts a quasi face-on disk (see Figure 1), while the dust absorption will mimic a stellar depleted core. The observational evidence that the vast majority of LLAGNs are associated to circumnuclear dust (González Delgado et al. 2008) further complicates this picture. Given that core galaxies are such an ideal benchmark to study those objects, it is of paramount importance to disentangle any role of the dust in producing central flattenings in the surface brightness distribution.

The study of dust components in galaxies has been significantly progressing during the last two decades. Not only the influence of dust over the kinematics of both late- and early-type galaxies has been ascertained (e.g. Baes & De Jonghe 2002; Baes et al. 2003), but radiative transfer codes have shown how dust biases the observed bulge/disk structural parameters (e.g. Gadotti, Baes, & Falony 2010). In particular, radiative transfer modelling has been extensively applied to perform surface brightness fitting of dust-obscured, edge on disk galaxies (e.g. Emsellem 1995; Xilouris et al. 1999; Baes et al. 2010; De Looze et al. 2012; Vieane et al. 2015) with the aim of characterizing the galaxy’s spectral energy distribution and hence the source of dust heating, or addressing the so-called energy balance issue (e.g. Saftly et al. 2015, and references therein). Here we intend to adopt a similar approach to solve the core/AGN/dust ambiguity in ETGs. We propose a new, simple, but powerful methodology to derive central dust geometries and masses. The technique involves creating, using a radiative transfer code, a pool of model images of the galaxy in which the effects of dust are taken into account. These 3D models are projected on the field of view to produce the 2D surface brightness models, which are then compared with the actual image. In this way we can infer the bona-fide dust distribution. One immediate application (among others) is to distinguish central point sources into actual AGNs and those superimposed to a core-like AGN. Specifically, their central sources have a reported luminosity of $\log(L_X[\text{erg s}^{-1}]) = 39.2$ (NGC 4552) and $\log(L_X[\text{erg s}^{-1}]) = 38.8$ (NGC 4494) in the 2–10 keV band (González-Martín et al. 2009), classifying them as LLAGNs. Moreover, for NGC 4552 Xu et al. (2005) report an X-ray variability timescale of $\sim$1 hr, while Maoz et al. (2005) and Cappellari et al. (1999) report long-term variability in the UV bands. Finally, in their analysis of the 1D surface brightness profile of NGC 4552 in the $HST$ bands, Cappellari et al. (1999) and Dullo & Graham (2014) fit the central bump with a point-like component (although in Section 4 we argue this is an artefact of dust extinction).

The images for the sample galaxies were retrieved from the Hubble Legacy Archive (HLA)\footnote{https://hla.stsci.edu}: their sublime spatial resolution ($\sim$0.15′′ Gaussian FWHM) is ideal for the study of the small (tens of pc) dust structures we intended to characterize. We chose blue bands, in which the effects of dust extinction are maximized; nominally the ACS/F475W and WFCPC2/F555W filters for NGC 4552 and NGC 4494, respectively. We sought for the image with the largest exposure time in the respective band, however the deepest image for NGC 4494 in the F555W filter is corrupted right at the center of the dust ring (probably due to an incorrect exposure combination), hence we used the second best. The details of the data set are provided in Table 1.

3 MODELLING OF DUST RINGS
Our technique for the modelling of dusty structures is composed of two steps. The first requires to parametrize the ‘pure’ stellar profile of the galaxy, i.e. as if the dust component was not present (Section 3.1). In the second step, different dust geometries and masses are embedded within the pure stellar profiles, generating a library of dust-absorbed models. These models, generated through radiative transfer prescriptions, are then fitted (scaled in intensity and matched in x,y position) to the original galaxy image. The best fitting model automatically selects the bona-fide dust properties (Section 3.2). The stellar surface brightness fitting and the dust-absorbed model fitting are both performed in two dimensions (2D), in order to allow us to account for the rotation angles of the dust rings. The obvious name of choice for our pipeline — in line with the geezy formalism of astronomers — was ‘Lord Of The Rings’ (LOTIR).

2 SAMPLE AND DATA
The test galaxies for our study are NGC 4552 (M 89, UGC 7760, VCC 1632; Virgo) and NGC 4494 (UGC 7662; Coma). Deep $HST$ images clearly revealed that these objects host central disk- or ring-like dust structures (see Figure 1). In particular, NGC 4552 hosts a quasi face-on disk surrounded by several dust streams which spread radially beyond the effective radius of the galaxy (Ferrarese et al. 2006). The structure in NGC 4494, first observed by Forbes, Franx, & Illingworth (1995), resembles instead a more edge-on ring, or better a torus with a large inner hole and a small opening angle. These two objects have been chosen from the ensemble of dust-rich ETGs of Lauer et al. (2005, their Figure 1) in order to be representative of the two classes of core (NGC 4552) and core-less (NGC 4494) galaxies, according to the central classification provided by the same authors. In particular, the core size of NGC 4552 was estimated in 0.49′′ (42.5 pc).

An additional criterion for the choice of our test galaxies was to host faint AGNs. Specifically, their central sources have derived luminosity of $\log(L_X[\text{erg s}^{-1}]) = 39.2$ (NGC 4552) and $\log(L_X[\text{erg s}^{-1}]) = 38.8$ (NGC 4494) in the 2–10 keV band (González-Martín et al. 2009), classifying them as LLAGNs. Moreover, for NGC 4552 Xu et al. (2005) report an X-ray variability timescale of $\sim$1 hr, while Maoz et al. (2005) and Cappellari et al. (1999) report long-term variability in the UV bands. Finally, in their analysis of the 1D surface brightness profile of NGC 4552 in the $HST$ bands, Cappellari et al. (1999) and Dullo & Graham (2014) fit the central bump with a point-like component (although in Section 4 we argue this is an artefact of dust extinction).

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3.1 Modelling of galaxian light profile

The software of choice for the 2D fitting of the surface brightness of the sample galaxies was GALFIT (Peng et al. 2010). An important caveat is that, in order to infer the pure stellar profiles, the central areas affected by dust absorption are to be accurately masked. Differently from the ‘canonical’ approach of solely masking the dust features (i.e. the ring) and leaving the innermost bright areas un-masked, we rejected the whole area contained within the outermost edge of the ring. This is because the luminosity of the bright areas inside the ring does not only depend on the stellar/AGN light, but it is also determined by the geometry of the dust (e.g. the size of the inner hole) and by the reflection on the ring itself. It is therefore not correct to use central data to fit parametric models accounting solely for stellar/AGN emission. Unfortunately, many past studies inaccurately overlooked this caveat, with the result of incorrectly identifying non-existing galaxy cores or central point sources, as discussed in Section 4.

Apart from the complete masking of the central dust feature, the rest of the GALFIT analysis reflected the ‘standard’ 2D fitting routine (see e.g. Bonfini & Graham 2016). In brief, necessary corollary images are: the point spread function (PSF), the uncertainty (‘sigma’) map, and the contaminant objects mask. For the PSFs, we used the TinyTim tool (Krist et al. 2011), which allows to generate ray-traced point spread functions for the HST instruments; in particular, we generated the PSFs corresponding to the pixel positions corresponding to the center of the sample galaxies, to which we were most interested. In our experience, the TinyTim PSFs usually slightly underestimate the seeing by a few percent, but in our images there were not enough suitable stars to produce a data-generated PSF. The sigma images were generated by the internal Poissonian algorithm of GALFIT, to which we provided the background level and root-mean-square (RMS), which we measured on background images created through SEXTRACTOR (e.g. Bertin & Arnouts 1996). Contaminant objects were identified and masked starting from the SEXTRACTOR ‘segmentation’ maps: these are FITS images in which every pixel deemed part of a source is masked out, essentially creating a map of the detected objects. We run SEXTRACTOR twice (and combined the results), first tuned to identify extended contaminant objects, and then to detect smaller objects embedded in the galaxy light. Through a Perl script we expanded isometrically the borders of each object in the segmentation images, hence aggressively masking all possible contaminants. Such masks were integrated with the dust masks described above, and with the hand-made masks for problematic objects.

The fitting box was fixed to 400″×400″ for both galaxies. This range was chosen as the best compromise between the ability of correctly reconstructing the galaxian light profile (whose inward extrapolation will, in the next step, be affected by dust absorption), and the computational time required by the radiative transfer code to reproduce images of the same size (see Section 3.2). In this context, it is important to remember that the single orbit HLA mosaics of nearby galaxies are known to be background subtracted, due to the relative extent of the galaxies with respect to the field of view of the cameras. Additionally, the WFPC2 mosaics suffer of the additional issue of bias discontinuity between its 4 CCDs (see discussion in Bonfini 2014). Both of these features manifest as sharp turn-downs in the light profiles at large radii, which we avoid with our choice of fitting box.

For NGC 4552 we fit a simple Sérsic component (under the assumption that the galaxy does not host a core nor a central AGN), while for NGC 4494 we adopt a Sérsic + exponential halo component. The choice for a single/double component model is strongly supported by the kinematics of the galaxies: while NGC 4552 shows a homogeneous velocity dispersion pattern (Krajinović et al. 2011), NGC 4494 present a double structure (Foster et al. 2011). The best-fit parameters are reported in Table 2.

3.2 Monte-Carlo simulation of dust geometry and 2D fitting

The 2D stellar parametric models obtained as described in Section 3.1 were used as input for the radiative transfer software, through which we added the dust component and recalculated the expected light emission. To this purpose, we used SKIRT (e.g. Camps & Baes 2015), a software which emulates the physical processes involving dust (scattering, absorption and emission) through a Monte Carlo technique. SKIRT allows the user to set-up two types of classes, i.e. the stellar and the dust components. Furthermore, the geometry of both classes can be modified in several ways by applying a set of “decorators”. A decorator is a way that SKIRT uses to implement changes in a given geometry (e.g. a “spiral arm” decorator applied to a disk geometry, will modified the density distribution of a disk in such a way to mimic logarithmic

| Target | RA (J2000) | Dec (J2000) | D | Camera/Filter | Exp. time | Prop. ID | Reference |
|--------|------------|------------|---|---------------|-----------|----------|-----------|
| NGC 4552 | 12:35:39.8 | +12:33:23 | 16.0 | ACS/F475W | 750 | 4901 |
| NGC 4494 | 12:31:24.1 | +25:46:31 | 13.7 | WFPC2/F555W | 1000 | 5454 |

Table 1. Details of the HLA products used in this work. These are sky-subtracted mosaics composed by same-orbit observations for each galaxy. (1) Target name. (2,3) Target coordinates from NED (J2000). (4) Target distance from NED. (5) HST camera and filter. (6) Exposure time. (7) Proposal ID for the archival observation. (8) First publication for the data set.
In developing our pipeline we first attempted to adopt the publicly available FitSKIRT (De Geyer et al. 2013); this is a genetic algorithm-based wrapper for SKIRT designed to automatically explore the parameter space and find the dust best-fitting structural parameters. However in our case, due to a very high degeneracy between the disk scale-heights and the inclination angles, using FitSKIRT turned out to be infeasible. In fact, either the fits were not converging, or the parameters for the dust disks turned out to be unphysical. The reason for this poor performance arguably lies in the fact that FitSKIRT has been constructed, tested, and optimized specifically to study edge-on spiral galaxies. We therefore designed our own approach, as described in the following.

To simulate our Sérsic (+ exponential halo) stellar components we used the SKIRT built-in Sérsic class, to which we applied a ‘rotation’ and a ‘triaxial’ decorator to reproduce the observed position angle (P.A.) and ellipticity (e), respectively. In this context, we were only interested in reproducing the projected appearance of the galaxy rather than its three-dimensional geometry, to which the SKIRT decorators formally applies. At the center of these stellar components we added the SKIRT dust components. Their geometries were chosen after a careful visual inspection of the dust features and of their reflection patterns, and after testing with different models. For NGC 4552 we adopted the Skirt ‘disk’ component, of the form:

$$\rho(r, z) = \rho_0 \exp\left(-\left(r/h_r + z/h_z\right)^2\right) \quad \text{for} \quad r > r_{i,d}$$  \hspace{1cm} (1)$$

where $h_r$ and $h_z$ are the radial and vertical scale lengths, $r_{i,d}$ is the size of the inner truncation, and $\rho_0$ is the central density (equivalently determined by the total dust mass $M_{dust}$), i.e. the innermost density of the exponential profile was it not truncated by the inner hole. For the case of NGC 4494 we opted instead for the Skirt ‘torus’ decorator.

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4 The description of all available classes/decorators is accessible online, on the project website: www.skirt.ugent.be/root/index.html.

5 Note that an exponential function is equivalently described by a Sérsic with index $n = 1$.
characterized by the inner \( r_{i,t} \) and outer \( r_{o,t} \), radii, the radial density power-law index \( p \), the polar index \( q \), the opening angle \( \Delta \theta \) (i.e. the vertical angular extent as seen from the center of the torus), and the normalization parameter \( A \) (equivalently determined by \( M_{\text{dust}} \)). Dependencies of the dust density on the polar angle where ignored by keeping the \( q \) parameter fixed to 0. For both galaxies we adopted a dust mixture following the prescriptions of Zubko, Dwek, & Arendt (2004); these account for a composition of graphite, silicate, and neutral and ionized PAH dust grains, and are calibrated over the dust emission, extinction and abundance of dust in the Milky Way.

We visually chose and fixed the angles by which the central dusty structure is rotated with respect to the line of sight of the observer. In principle, rotation angles are degenerate with the disk/torus thickness, but since the structures turned out to be physically thin (see Table 3), the error we introduced by locking the angles was marginal and was abundantly compensated by a significant speeding-up of the simulations. All the other dust parameters were allowed to vary with the exception of the torus index \( p \), which we set to 1. We tentatively chose first guess parameters by visually inspecting the images and producing a number of models to get fairly close to the observed surface brightness profile. Hence, we defined a grid in the parameter space that we sampled with discrete values by varying each parameter to within a factor of 2 from its initial best guess. For each combination of parameters we created a SKIRT model, which we subsequently convolved with the TinyTim PSF (Section 3.1) corresponding to the seeing of the instrument we intended to simulate, hence creating a ‘library’ of dust-absorbed models. Each sampled model was then fit to the original galaxy image using GALFIT, to which we provided — for consistency — the same error images utilized during the previous surface brightness fitting step (Section 3.1). However, for this part of the procedure we used a mask which left uncovered only an area centered on the ring and roughly doubling its size (dashed circles in Figure 1), since we wanted to focus our fit on the central region. In fact, since the parametric stellar component provided to SKIRT is exactly what was fitted in the real image, it automatically reproduced the outer galactic light. To obtain the best-fit model, we simply performed a \( \chi^2 \) search of the sampled parameter space.

The parameter uncertainties were estimated based on the RMS of the residuals, according to the following procedure. First we evaluated — for the best-fit model — the ‘on-source’ RMS \( \text{RMS}_S^{\text{best}} \), i.e. the RMS of the residuals within the fit area, and the ‘background’ RMS \( \text{RMS}_B^{\text{best}} \), i.e the RMS evaluated over the pixels outside the fit area. Then, we selected a pool of models whose on-source RMS \( \text{RMS}_S \) was such that:

\[
\text{RMS}_S < \text{RMS}_S^{\text{best}} + 3 \times \text{RMS}_B^{\text{best}}
\]

i.e. less than three times above the residual background noise. Finally, the upper and lower uncertainties for each parameter were respectively defined as the maximum and minimum values of that parameter within the pool of selected models. Due to the relatively scarce sampling of the parameter space, dictated by the required computational time, for several parameters we could only identify upper or lower limits. The best-fit parameters for the dust components, and their uncertainties, are reported in Table 3.

In Figure 1 we show the original, the best-fit model, and the residual (data – model) images. A 1D projection of the results is presented instead in Figure 2. For NGC 4494, the best-fit model selected by LOTR (including exclusively stellar and dust components) underestimates the innermost \( (R < 0.2''^\prime) \) surface brightness by ~0.3 mag. This discrepancy is most probably due to the presence of a faint central point source, which we interpret as a LLAGN (Section 4.1). To test this, we added a \( 5 \times 10^6 \, L_\odot \, (\sim 1.5 \times 10^{40} \text{ erg sec}^{-1}) \) point source at the center of the dust-absorbed model, and then re-run the 2D fit in order to fine tune the new model.

![Figure 1](https://example.com/figure1.png)

**Figure 1** Original model (dashed), best-fit model (medium gray), and residual (data – model) images. A 1D projection of the residual images is also shown. The effects of the AGN are most evident in the fits to NGC 4552 (top) and NGC 4494 (bottom). The AGN we added (point-like) is not ‘shaded’ by the dust. Moreover, its modest luminosity does not produce any significant reflection over the dusty torus. Our analytical approach of treating the AGN as a post-sampling additional component is therefore justified.

### 4 DISCUSSION

#### 4.1 Dust pretending to be a core or an AGN

The most surprising result of our analysis is the discovery that, once the effect of dust is properly taken into account, NGC 4552 is not compatible with hosting a core, as previously claimed by several studies. Notably, the fact that NGC 4552 presents strong signs of ‘fine structure’ (i.e. indications of recent interactions Schweizer & Seitzer 1992) is potentially compatible with the lack of a [large] core (Bonfini et al. 2017). However, NGC 4552 has been classified as a ‘core’ galaxy by Faber et al. (1997), Richings, Uttley, & Kording (2011), Rusli et al. (2013), Dullo & Graham (2014), apart from the reference study we used to select our sample, i.e. ster et al. (2005). The core was confirmed even when the analysis included image correction by dust extinction (e.g. Ferrarese et al. 2006). This indicates how easy it is to misclassify dust rings as cores — how could this galaxy deceive so many investigations? Excluding the early works, in which the concept of ‘core’ was still under debate, one possible explanation is that the aforementioned studies regarded large samples, over which a detailed object-by-object investigation is not feasible. However, we believe that the main source of discrepancy lays in their use of 1D analysis. With this technique, dust features are masked on the images and then the surface brightness profiles extracted; since this procedure inevitably averages the intensity over isophotes, it is admittedly difficult to keep track of the (asymmetric) dust extinction at the fitting stage.

Dullo & Graham (2014) measured a \( V \)-band point source magnitude \( m_V = 20.6 \, \text{mag} \), corresponding to \( \sim 10^6 \, L_\odot \).
Figure 1. Final results of our LOTR fitting pipeline for NGC 4552 (top), and NGC 4494 (bottom). Left — Original HLA images. The dashed circles represent the areas over which the fitting of the dust-absorbed models was performed, and correspond to an angular radius of 1″ for NGC 4552, and 2″ for NGC 4494. They also roughly correspond to the areas masked in the first step of LOTR (Section 3.1) during which we were interested in modelling the stellar emission avoiding all possible extinction by dust. Center — Best-fit dust-absorbed model generated through Skirt using the stellar components determined from the surface brightness fit to the galaxies (Table 2; Section 3.1), and the best-fit dust components from our Monte-Carlo simulation (Table 3; Section 3.2). Right — Data minus model residuals expressed in terms of surface magnitude difference ($\Delta \mu$). The color map scaling has been chosen in order to match the corresponding $\Delta \mu$ range in the bottom panel of Figure 2, from which it is clear that the represented surface brightness fluctuations are well below 0.1 mag/arcsec$^2$. The bright “stripes” in the residual image for NGC 4552 are not artefacts, but rather correspond to real dust lanes.

Note: The images for NGC 4494 refer to the model including the AGN component (blue data series in Figure 2).

similar to what Cappellari et al. (1999) measured in their HST-F342W band. From an other point of view, given that the point sources in NGC 4494 and NGC 4552 have similar X-ray emission (Section 2), and assuming a similar X-ray to optical emission ratio, we can reasonably expect that they also possess a similar optical luminosity, i.e. $\sim 5 \times 10^9 L_\odot$ (see Section 3.2). However, when we added a point source of such luminosity at the center of our NGC 4552 best-fit model — similarly to what we did for NGC 4494 — the fit residuals showed no statistical improvement. We argue that the point source ‘detected’ in the aforementioned studies was an artefact of incorrectly assuming a core in NGC 4552. In our physically simpler scenario, the central peak ($R < 0.15''$) is merely due to stellar emission shining through the inner hole of the dust disk (plus reflection of stellar light on the dust). In the UV band, in which the dust extinction is more significant, the contrast between the radiation passing through the hole and that absorbed by the disk is expected to be enhanced. We hence believe that the fluxes of the UV ‘spikes’ (as they named the central emission) measured by Cappellari et al. (1999) are particularly affected by this problem. In general, neglecting dust extinction can lead to a strong overestimation of the luminosity of the AGN, or even to a false detection in optical/UV bands.

Cappellari et al. (1999) additionally studied the evolution of the central ‘spike’ of NGC 4552 during the period 1991–1996, and they recorded significant intensity variation in the HST UV bands (following on the UV flare observed by Renzini et al. 1995), up to a factor $\sim 4.5$ (during the interval 1991–1993). This figure is surprisingly high with respect to the fluctuations observed in optical/UV surveys of AGNs (e.g. Simm et al. 2016). They suggest that this behaviour should be related to a sporadic accretion event over the central black hole. We argue that at least part of the variability that Cappellari et al. (1999) measured was significantly affected by the temporal variations of the instrumentation on board HST. Most notably, in between their 1991 and 1996 observations the Corrective Optics Space Telescope Axial Replacement (COSTAR) was mounted and calibrated. We wish to stress that — although the authors took great care
Figure 2. Projection of the 2D data, model, and residual images of NGC 4552 (left), and NGC 4494 (right), performed over concentric circular annulii. We stress that these plots do not represent the result of a fit to the 1D data series, but rather an azimuthally averaged representation of Figure 1. The projections extend further than the images of Figure 1, and they actually cover the whole radial range fitted with Galfit in the first step of the LOTR pipeline (Section 3.1). Top — Surface brightness profiles of the data (empty circles) and of the best-fit models identified with our pipeline (green circles). For NGC 4494, we additionally show (blue circles) the profile generated by adding an arbitrarily luminous AGN at the center of the best-fit dust-absorbed model, and re-performing the 2D fit. Bottom — Surface magnitude difference (Δµ). The Δµ RMS value (⟨Δµ⟩) is indicated in the plot, and in the case of NGC 4494 it refers to the model without the AGN component.

Figure 3. Radial colour profiles of the sample galaxies. The color coding is proportional to the colour value and meant to emphasize the reddening by the dust rings, which manifests as a red “bump” in the profile. The colours have been calculated in the original HST filters, and they roughly correspond to the SDSS $g′ - z′$ ($F475W - F850LP$) and Johnson-Cousins $V - I$ ($F555W - F814W$).

In calibrating their frames — these instrumental variations of the PSF and sensitivity could have alone mimicked AGN variability. Was the variability real, the suggested hypothesis of a sporadic accretion or even of a UV flare from a star stripped from its envelope are not hypothesis at odds with our model: the radiation released by these events can actually shine through the central hole of the dust ring, similarly to the LLAGN in NGC 4494; Section 3.2). However, these events are relatively rare occurrences. In our paradigm, variability could simply be due to a dust cloud crossing the line of sight or to a change in the inner geometry of the dust ring, such as a variation in ‘clumpiness’, in the size of the hole, or in the dust density (although the timescales for a change in the dust configuration would imply extremely high velocities). For example, by (erroneously) fitting a core-Sérsic + PSF model to our best-fit model, and to a model in which we just changed the best-fit vertical disk length ($h_z = 0.5$ pc) to its upper limit ($h_z = 1.3$ pc; Table 3), the flux encompassed by the PSF changes by a factor ~2.5, close to the measurements of Cappellari et al. (1999). This possibility is a simpler alternative to an AGN in explaining the optical/UV variability observed in the central emission of NGC 4552. In conclusion, despite NGC 4552 shows X-ray variability (Xu et al. 2005) and emission line indications for...
AGN activity (e.g. Ho, Filippenko, & Sargent 1997; Véron-Cetty & Véron 2010), we argue that this might be below detection levels in optical/UV imaging. The case for NGC 4494 is less controversial. Of the studies which attempted to fit both core and core-less models to their sample galaxies, only one (Rest et al. 2001) preferred not to doubtlessly classify the galaxy as core-less, due to the presence of the dust ring. Our results further confirm that the central decrease in intensity (with respect to the extrapolation of the outer light profile) is purely due to extinction. NGC 4494 hosts a LLAGN (e.g. Véron-Cetty & Véron 2010) with $L_{5100} \sim 4 \times 10^{41}$ erg s$^{-1}$, and $L_{X}$ is the X-ray luminosity, and $L_{X}$ and $L_{V}$ are the X-ray and V-band luminosities, respectively. Combined, these scaling relations yield: $L_{V} = 1.1 \times L_{X}$; this is too little to explain the factor of 10 between our V-band luminosity and the X-ray one. However, the relations by Elvis et al. (1994) were calibrated over luminous AGNs, and they might be very different for LLAGNs. Unfortunately, even assuming that for LLAGNs $L_{bol} \sim 30 \times L_X$ (Marconi et al. 2004, their equation 21) and keeping valid the previous $L_{bol} - L_V$ relation, we could reach $L_V \sim 2 \times L_X$, which is still quite far from our estimate. One possible explanation compatible with our results is that the AGN is Compton-thick: in that scenario one can expect up to $L_X^{\text{intrinsic}} \sim 60 \times L_X^{\text{observed}}$ (Panessa et al. 2006), which would render the calculation broadly consistent with our $L_{F555W}$.

As a further check for discerning the effects of dust extinction as opposed to the presence of a core, we created color maps for the sample galaxies. To do so, we additionally retrieved the F850LP and F814W images from the HLA archive, and used them to produce maps in the $F475W$--$F850LP$ and $F555W$--$F814W$ colours, roughly equivalent to the SDSS $g'$--$z'$ and Johnson-Cousins $V$--$I$ colours, respectively. In Figure 3 we show a radial profile extracted from those colour maps along the same concentric annuli utilized to produce Figure 2. If the inner flattening in the radial surface brightness profiles of Figure 2 were due to the presence of a core we would expect no corresponding signature in the radial colour profile, since the scouring action of a SMBH binary would not preferentially remove stars of a larger/smaller mass. On the contrary, in Figure 3 we observe — for both galaxies — a well defined “bump” corresponding to the physical extent of the rings (compare with central panels of Figure 1). For NGC 4494 we further observe that the innermost $\sim 20$ pc are significantly bluer than the outer profile: this feature is compatible with the emission by an accreting disc and hence supports our previous statement about the presence of a faint AGN.

Finally, we wish to stress that the dust rings described in this work shall not be confused with the torus surrounding the AGN (although they are plausibly the large-scale source of material for the accretion disc). We show this by demonstrating that the inner radius of a torus is way smaller than what we observe in our dust rings. The inner radius of an AGN torus ($r_{sub}$) is dictated by dust sublimation, and can be calculated as (Nenkova et al. 2008):

$$r_{sub} \sim 0.4 \left( \frac{L}{10^{45} \text{ erg s}^{-1}} \right)^{1/2} \left( \frac{1500 \text{ K}}{T_{sub}} \right)^{2.6} \text{ pc}$$

where $L$ is the AGN luminosity and $T_{sub}$ is the dust sublimation temperature. By using a luminosity of $10^{49}$ erg s$^{-1}$ (as is the case for the LLAGNs in our galaxies) and adopting the standard $T_{sub} = 1500$ K, we obtain $r_{sub} \sim 0.001$ pc. This size is at least 2 orders of magnitude lower than what we measure for our ring holes (Table 3). This simple test shows how the rings we observed are structures much larger than an AGN torus.

### 4.2 Evolution of dust rings and LLAGNs in ETGs

Dust structures are very common in ETGs (e.g. Tran et al. 2001); their morphology ranges from large-scale disks (such as in the famous case of the Sombrero galaxy), to filaments, to inner disk rings. Numerical simulations have shown that molecular disks result quite naturally from wet mergers (e.g. Xu, Narayanan, & Walker 2010), although recent integral field spectroscopy results have shown that ETGs do not necessarily require to accrete their dust content from merger events (e.g. Bassett et al. 2017). These studies mostly concern large-scale structures, while the cases of inner rings similar to those presented in this paper remain still mysterious.

Lauer et al. (2005) interpreted the compilation of dust phenomenology in their sample of ETGs in evolutionary terms: they argued that the fate of dust structures is inevitably to in-fall and settle at the center of the galaxy (independently of their origins) in ‘episodic’ events. They support this theory with the observation that galaxies hosting well defined inner rings are elsewhere devoid of dust.

With no intention of generalizing (given the limited sample analysed in this work) we discuss here whether this scenario might be plausible for our objects; NGC 4552 shows clear signs of disturbance in its extended light profile — in fact, it hosts a faint shell and a stellar stream (e.g. Schweizer & Seitzer 1992) — while NGC 4494 does not present any evident ‘fine structure’. By relating the fine structure to the time elapsed form the last merger (e.g. Bonfini et al. 2017), we can hence infer that NGC 4552 is dynamically ‘younger’ than NGC 4494, or, in other words, that the potential of the latter is more relaxed than that of the former. This observation, combined with the fact that NGC 4552 still hosts dust lanes and that its ring is less defined than that of NGC 4494 (Figure 1), might imply that dust settling is strictly related to the overall evolution of the gravitational potential.

One representative comparison for our galaxies is NGC 4261, hosting the prototypical, and arguably most studied dust disc in an ETG, first observed by Jaffe et al. (1996). These authors reported that the disc has a major-axis extent of 1″.79, which at the distance of NGC 4261 (29.4 Mpc; Jensen et al. 2003) corresponds to a physical size of $\sim 250$ pc, a thickness $\lesssim 20$ pc, and an opening angle of $\sim 10^\circ$. The galaxy has a prolate stellar geometry (Davies & Birkinshaw 1986), and displays boxy isophotes (Schweizer & Seitzer 1992), but otherwise shows no sign of a past merger, although the spatial distribution of its globular clusters hints toward a recent fly-by interaction (Bonfini et al. 2017).
2012). The dust geometry in NGC 4261 is clearly larger than the rings observed in our sample galaxies. However, the similar opening angle/thinness of the respective disks, and the similarly relaxed potential of the galaxies suggest that the structure in NGC 4261 might be a scaled-up version closer to that observed in NGC 4494 rather than that of NGC 4552. The dust mass of the disk of NGC 4261 is estimated to be \( \log(M_{\text{dust}}/M_\odot) = 4.7 \) (Ferrarese, Ford, & Jaffe 1996) while its AGN has a luminosity \( \log(L_X [\text{erg} \cdot \text{s}^{-1}]) = 41.1 \) in the 2–10 keV band (Zezas et al. 2005). Hence, both its dust mass and X-ray luminosity are about 2 orders of magnitude larger than for our sample galaxies: this hints to a direct connection between the dust mass contained in the ring and the activity of the AGN.

As a final remark we observe that, despite the two galaxies show rings with similar mass and host LLAGNs of similar luminosity, their geometries are very different in size. The most striking difference is that the ring hole in NGC 4552 is much smaller than that of NGC 4494. This might be related to a different evolutionary state. However, in order to further explore and constrain this connection, the methodology presented in this work shall be applied to the study of a larger sample.

5 SUMMARY AND CONCLUSIONS

Many ETGs exhibit a variety of dust features, and most notably inner ring structures (Figure 1). From an observational point of view, dust ring extinction can deeply modify a galaxian surface brightness distribution. To study the properties of the dust and its effects on the imaging we created ‘Lord Of The Rings’ (LOTR), a pipeline which performs 2D fitting to galaxy images using surface brightness models which account for the effects of dust (both absorption and scattering). Our pipeline acts in two steps. At the first stage, it uses the 2D surface brightness modelling code GALFIT to determine the bona-fide unabsorbed stellar distribution (Section 3.1). At the second stage, it uses the radiative transfer code SKIRT to generate a library of dust-absorbed stellar distributions sampling the dust mass and dust geometry parameters. These models are fit to the original image and the best-fit model is identified via a simple \( \chi^2 \) statistics (Section 3.2).

We applied our methodology to NGC 4552 and NGC 4494, two ETGs reported to host LLAGNs, and initially chosen to be representative of the core and core-less class (respectively). However, our analysis revealed that NGC 4552 does not host a core nor shows photometric indications for a central AGN — at variance with previous studies based on similar optical imaging. Instead, it showed that dust-obscuration mimicked the presence of a core, while the central point-like luminosity was simply motivated by the infalling dust is currently reaching the galaxy center and it is just now turning on the AGN engine (small hole), or instead just now turning on the AGN engine (small hole), or instead because 2) past feedback has pushed away the surrounding material and hence the AGN is currently fading out due to starvation (large hole).

An application of our methodology to a large collection of dust ring galaxies (such as those reported by Lauer et al. 2005 or Tran et al. 2001) will yield the first coherent parametrisation of central dust structures, and hence provide important constraints on galaxy evolution. More generally, our methodology can be used to ‘expose’: 1) dust-obscured objects disguised as core galaxies, and 2) stellar emission (shining through dust ring holes) disguised as a point-like AGN.

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REFERENCES

Baes M., Dejonghe H., 2002, MNRAS, 335, 441
Baes M., et al., 2003, MNRAS, 343, 1081
Baes M., et al., 2010, A&A, 518, L39
Bassett R., et al., 2017, MNRAS, 470, 1991
Bonfini P., Bitsakis T., Zezas A., Duc P.-A., Iodice E., Gonzalez-Martin O., Bruzual G., Gonzalez Sanoja A. J., 2017, arXiv, arXiv:1710.05025
Bonfini P., Graham A. W., 2016, ApJ, 829, 81
Bonfini P., 2014, PASP, 126, 935
Bonfini P., 2014, PASP, 126, 935
Bonfini P., Zezas A., Birkinshaw M., Worrall D. M., Fabbiano G., O’Sullivan E., Trinchieri G., Wolter A., 2012, MNRAS, 421, 2872
Bertin E., Arnouts S., 1996, A&AS, 117, 393
Camps P., Baes M., 2015, A&A, 9, 20
Cappellari M., Renzini A., Greggio L., di Serego Alighieri S., Buson L. M., Burstein D., Bertola F., 1999, ApJ, 519, 117
Davies R. L., Birkinshaw M., 1986, ApJ, 309, L67
De Geyter G., Baes M., Fritz J., Camps P., 2013, A&A, 550, A74
De Geyter G., Baes M., Fritz J., Camps P., 2013, A&A, 550, A74

MNRAS 000, 1–10 (2017)
De Looze I., Baes M., Fritz J., Verstappen J., 2012, MNRAS, 419, 895
Dullo B. T., Graham A. W., 2014, MNRAS, 444, 2700
Elvis M., et al., 1994, ApJS, 95, 1
Emsellem E., 1995, A&A, 303, 673
Faber S. M., et al., 1997, AJ, 114, 1771
Ferrarese L., et al., 2006, ApJS, 164, 334
Ferrarese L., Ford H. C., Jaffe W., 1996, ApJ, 470, 444
Forbes D. A., Franx M., Illingworth G. D., 1995, AJ, 109, 1988
Foster C., et al., 2011, MNRAS, 415, 3393
Gadotti D. A., Baes M., Falony S., 2010, MNRAS, 403, 2053
González Delgado R. M., Pérez E., Cid Fernandes R., Schmitt H., 2008, AJ, 135, 747
González-Martín O., Masegosa J., Márquez I., Guainazzi M., Jiménez-Bailón E., 2009, A&A, 506, 1107
Graham A. W., 2016, ASSL, 418, 263
Ho L. C., 2008, ARA&A, 46, 475
Ho L. C., Filippenko A. V., Sargent W. L. W., 1997, ApJS, 112, 315
Jaffe W., Ford H., Ferrarese L., van den Bosch F., O’Connell R. W., 1996, ApJ, 460, 214
Jensen J. B., Tonry J. L., Barris B. J., Thompson R. I., Liu M. C., Rieke M. J., Aihara E. A., Blakeslee J. P., 2003, ApJ, 583, 712
Kormendy J., Fisher D. B., Cornell M. E., Bender R., 2009, ApJS, 182, 216
Krajnović D., et al., 2011, MNRAS, 414, 2923
Krist, J. E., Hook, R. N., & Stoehr, F. 2011, Proc. SPIE, 8127
van Langevelde H. J., Pihlström Y. M., Conway J. E., Jaffe W., Schilizzi R. T., 2000, A&A, 354, L45
Lauer T. R., et al., 2005, AJ, 129, 2138
Lauer T. R., et al., 2007, ApJ, 664, 226
Maoz D., Nagar N. M., Falcke H., Wilson A. S., 2005, ApJ, 625, 699
Marconi A., Risaliti G., Gilli R., Hunt L. K., Maiolino R., Salvati M., 2004, MNRAS, 351, 169
Nenkova M., Sirocky M. M., Nikutta R., Ivezić Z., Elitzur M., 2008, ApJ, 685, 160-180
Panessa F., Bassani L., Cappi M., Dadina M., Barcons X., Carrera F. J., Ho L. C., Iwasawa K., 2006, A&A, 455, 173
Peng C. Y., Ho L. C., Impey C. D., Rix H.-W., 2010, AJ, 139, 2097
Renzini A., Greggio L., di Serego Alighieri S., Cappellari M., Burstein D., Bertola F., 1995, Natur, 378, 39
Rest A., van den Bosch F. C., Jaffe W., Tran H., Tsvetanov Z., Ford H. C., Davies J., Schafer J., 2001, AJ, 121, 2431
Richings A. J., Utley P., Körding E., 2011, MNRAS, 415, 2158
Rusli S. P., Erwin P., Saglia R. P., Thomas J., Fabricius M., Bender R., Nowak N., 2013, AJ, 146, 160
Saftly W., Baes M., De Geyter G., Camps P., Renaud F., Guedes J., De Looze I., 2015, A&A, 576, A31
Schweizer F., Seitzer P., 1992, AJ, 104, 1039
Simm T., Salvato M., Saglia R., Ponti G., Lanzuisi G., Trakhtenbrot B., Nandra K., Bender R., 2016, A&A, 585, A129
Tran H. D., Tsvetanov Z., Ford H. C., Davies J., Jaffe W., van den Bosch F. C., Rest A., 2001, AJ, 121, 2928
Véron-Cetty M.-P., Véron P., 2010, A&A, 518, A10
Viaene S., et al., 2015, A&A, 579, A103
Zezas A., Birkinshaw M., Worrall D. M., Peters A., Fabbiano G., 2005, ApJ, 627, 711
Zubko V., Dwek E., Arendt R. G., 2004, ApJS, 152, 211
Xilouris E. M., Byun Y. J., Kylafis N. D., Papaconstantopoulos A., 1999, A&A, 344, 868
Xu Y., Xu H., Zhang Z., Kundu A., Wang Y., Wu X.-P., 2005, ApJ, 631, 809
Xu X., Narayanan D., Walker C., 2010, ApJ, 721, L112