Heavily obscured quasar host galaxies at $z \sim 2$ are discs, not major mergers

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ABSTRACT
We explore the nature of heavily obscured quasar host galaxies at $z \sim 2$ using deep Hubble Space Telescope Wide Field Camera 3/infrared imaging of 28 dust-obscured galaxies (DOGs) to investigate the role of major mergers in driving black hole growth. The high levels of obscuration of the quasars selected for this study act as a natural coronagraph, blocking the quasar light and allowing a clear view of the underlying host galaxy. The sample of heavily obscured quasars represents a significant fraction of the cosmic mass accretion on supermassive black holes as the quasars have inferred bolometric luminosities around the break of the quasar luminosity function. We find that only a small fraction (4 per cent, at most 11–25 per cent) of the quasar host galaxies are major mergers. Fits to their surface brightness profiles indicate that 90 per cent of the host galaxies are either disc dominated, or have a significant disc. This disc-like host morphology, and the corresponding weakness of bulges, is evidence against major mergers and suggests that secular processes are the predominant driver of massive black hole growth. Finally, we suggest that the coincidence of mergers and active galactic nucleus activity is luminosity dependent, with only the most luminous quasars being triggered mostly by major mergers.

Key words: galaxies: active – galaxies: high-redshift – galaxies: Seyfert.

1 INTRODUCTION
Our view on which processes are important in triggering and fuelling black hole accretion phases has changed as the first rest-frame optical observations of $z \sim 2$ active galactic nucleus (AGN) host galaxies are being made with the new Wide Field Camera 3 (WFC3)/infrared (IR) on the Hubble Space Telescope (HST), Schawinski et al. (2011) used the Early Release Science observations of a sample of $1 < z < 3$ X-ray-selected moderate-luminosity ($10^{42} < L_X < 10^{44}$ erg s$^{-1}$) AGN to show that the majority of the host galaxies feature disc-dominated rest-frame optical light profiles, while showing no significant signs of mergers and interactions; this was recently confirmed by Kocevski et al. (2012) with a larger sample. AGN selected in X-rays trace the peak of black hole growth at moderate luminosities and therefore capture a significant fraction of cosmic black hole growth that results in normal black holes at $z \sim 0$, such as the black hole at the centre of the Milky Way (e.g. Ueda et al. 2003; Hasinger, Miyaji & Schmidt 2005). The fact that a large fraction of this black hole growth is not associated with major mergers, but rather with disc host morphologies, suggests that secular processes are most important in driving most black hole growth.

Where does this leave major mergers as drivers of black hole growth and spheroid formation? The major merger picture was initially based on the most ultraluminous starburst galaxies transitioning to powerful quasars. Specifically, simulations of gas-rich major mergers resulted in first obscured and then unobscured very luminous quasars. We now look at the host galaxies of heavily obscured quasar-luminosity AGN.

The classic merger picture was first outlined by Sanders et al. (1988): two gas-rich galaxies undergo a major merger, which in turn triggers a powerful, IR-luminous starburst as well as accretion on to the black hole. Once the accretion episode reaches quasar luminosity, the quasar by some means (radiation, outflows, winds, jets, etc.) drives out the gas, terminating both the starburst and the
quasar. Theorists have used this sequence as the basis for detailed simulations of merger-driven quasars and quenching, and it has become a major component of our understanding of galaxy evolution (Di Matteo, Springel & Hernquist 2005; Hopkins et al. 2005, 2006, 2008; Springel et al. 2005).

Heavily obscured quasars are the best place to investigate the role of major mergers in triggering quasars, for two reasons: (i) the obscuration acts as a natural coronagraph, blocking the quasar light so we are allowed a clear view on the host galaxy, and (ii) simulations predict that the heavily obscured phase coincides with the peak of morphological disturbance as the progenitor galaxies are conflated in a powerful starburst.

In this Letter, we present new WFC3/IR rest-frame optical imaging of $z \sim 2$ heavily obscured quasar host galaxies. The quasars selected have IR and inferred bolometric luminosities suggesting that they are just below or at the ‘break’ in the quasar luminosity function. This means that they represent a substantial fraction of cosmic black hole growth.

Throughout this Letter, we assume a $\Lambda$ cold dark matter ($\Lambda$CDM) cosmology with $h_0 = 0.7$, $\Omega_m = 0.27$ and $\Omega_{\Lambda} = 0.73$, in agreement with the most recent cosmological observations (Hinshaw et al. 2009).

2 OBSERVATIONS

2.1 Sample selection

We select heavily obscured quasars in the Extended Chandra Deep Field South (ECDFS) using the IR excess method developed by Fiore et al. (2008) (see also Treister et al. 2009). This method works by selecting intrinsically red objects using the observed $R - K$ colour with excess mid-IR emission seen in the $f(24 \mu m)/f(R)$ ratio. For this study, we use the canonical selection criteria of $R - K > 4.5$ and $f(24 \mu m)/f(R) > 1000$. Objects selected this way are known as dust-obscured galaxies (DOGs).

From stacking of X-rays, we know that more than 90 per cent of DOGs must be Compton thick ($N_H > 10^{24}$ cm$^{-2}$; $A_V > 30$–300) AGN (Fiore et al. 2008; Treister et al. 2009). Since the sample used here is a random subsample of the one used by Treister et al. (2009), we expect the AGN fraction to be comparable.

2.2 Hubble Space Telescope WFC3/IR imaging data

The Chandra Deep Field South has been imaged over 39 arcsec$^2$ using the WFC3/IR F105W, F125W and F160W filters by the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS; Grogin et al. 2011; Koekemoer et al. 2011). We obtained the six-epoch mosaic (exposure time approx. eight orbits) from the CANDELS website (http://candels.ucolick.org/) and cross-matched the F160W image with our DOG sample; this yields a total of 31 DOGs covered by the F160W image. We remove one object due to image artefacts. Because of the ongoing nature of the CANDELS observations, the exposure depth is not uniform across the field. We show postage stamps of the entire sample of 30 objects in Fig. 1 and summarize their properties in Table 1.

2.3 Mid-infrared and bolometric luminosities

We estimate the quasar bolometric luminosity in the DOG sample to place it in a cosmological context. Very few DOGs have spectroscopic redshifts (Treister et al. 2009) but their photometric properties place them in the redshift range $1 < z < 3$.

We convert the observed Spitzer MIPS 24 $\mu$m fluxes of the ECDFS DOGs from Treister et al. (2009) to intrinsic mid-IR luminosities by taking the median flux and assuming that it arises from a source at $z = 1$, 2 and 3, respectively, to span the plausible range. This yields observed $L_{24\mu m} = 8.1 \times 10^{43}$, $4.6 \times 10^{44}$ and $1.2 \times 10^{45}$ erg s$^{-1}$. Based on their observed (stacked) X-ray properties of DOGs, Treister et al. (2009) estimate typical bolometric luminosities of $L_{bol} \sim 10^{45}$ erg s$^{-1}$. Assuming a Elvis et al. (1994) quasar template redshifted to $z = 1$, 2 and 3 yields bolometric luminosities of $L_{bol} = 2.0 \times 10^{45}$, $1.1 \times 10^{46}$ and $7.4 \times 10^{46}$ erg s$^{-1}$, respectively. These estimates of the bolometric luminosity are imprecise; the 24-$\mu$m fluxes may contain at least some contribution from star formation, while the high levels of obscuration of the AGN indicate that even at 24 $\mu$m (rest frame $\sim$12$\mu$m) some fraction of the intrinsic AGN luminosity remains suppressed.

The compilation of the quasar bolometric luminosity function by Hopkins, Richards & Hernquist (2007) places the DOGs in context: they report a break at $L^* = 4.9 \times 10^{46}$ erg s$^{-1}$ at $z = 2$ meaning that the DOGs populate the break of the quasar luminosity function around the peak of accretion activity, or just below. The DOGs are...
thus part of the population where a substantial fraction of cosmic black hole growth occurs.

3 ANALYSIS

We inspect the F160W images of the 30 obscured quasar host galaxies to determine whether they could plausibly be major mergers. The images are shown in Fig. 1. We perform two separate analyses of the images: visual inspection and parametric fits to the light profiles. Two objects are too faint in the F160W image to be visually analysed (25379 and 27859).

3.1 Visual inspection

From visual inspection, there is one clear major merger amongst the sample: 29263. It features two distinct components and a prominent tidal tail. It resembles simulations of gas-rich disc–disc mergers (e.g. Barnes & Hernquist 1996; Di Matteo et al. 2005). Two further objects have features that can be interpreted as morphological disturbances: 28086 shows some asymmetry and 29372 may have two conspicuous asymmetric residual d features connected by tidal tails or similar features. 28086 shows some asymmetry and 29372 may have two conspicuous features connected by tidal tails or similar features.

Table 1. The sample of dust-obscured galaxies (DOGs).

| MUSYC ID | RA (J2000) | Dec. (J2000) | f(24 µm) (mJy) | Visual morphology | Sérsic index n | nL/HPS ratio | Residual image appearance |
|----------|------------|-------------|----------------|-------------------|----------------|-------------------|---------------------------|
| 25379    | 03:32:11.7 | −27:51:55.7 | 184.30         |                   | 2.74 ± 0.56     | −                 | –                         |
| 25783    | 03:32:18.6 | −27:51:34.3 | 324.90         |                   | 1.14 ± 0.23     | 0.91              | –                         |
| 27763    | 03:32:35.5 | −27:50:21.0 | 88.05          |                   | 1.00 ± 0.06     | −                 | –                         |
| 27859    | 03:32:10.1 | −27:50:33.0 | 305.10         |                   | −               | −                 | –                         |
| 28086    | 03:32:17.5 | −27:50:03.0 | 321.90         | Merger?           | 0.81 ± 0.04     | −                 | Asymmetric residual d     |
| 28338    | 03:32:44.8 | −27:49:54.0 | 155.00         |                   | 0.33 ± 0.06     | −                 | –                         |
| 29263a   | 03:32:44.3 | −27:49:11.9 | 262.50         | Major merger      | 0.62 ± 0.23     | 0.76              | –                         |
| 29263b   |            |             |                |                   | 1.69 ± 0.53     | 0.80              | –                         |
| 29372    | 03:32:35.7 | −27:49:15.9 | 569.30         | Merger?           | 0.51 ± 0.21     | 0.89              | Asymmetric residual d     |
| 29574    | 03:32:29.2 | −27:49:16.9 | 166.50         |                   | 0.90 ± 0.10     | −                 | –                         |
| 29632    | 03:32:17.3 | −27:49:08.1 | 88.76          |                   | 0.76 ± 0.06     | −                 | –                         |
| 30002    | 03:32:52.4 | −27:49:07.2 | 35.33          |                   | 2.49 ± 0.17     | −                 | –                         |
| 30246    | 03:32:45.9 | −27:48:55.6 | 26.79          |                   | 2.06 ± 0.08     | −                 | –                         |
| 30655    | 03:32:28.8 | −27:48:29.6 | 456.30         |                   | 0.78 ± 0.04     | −                 | Faint SF clumps            |
| 30821    | 03:32:24.3 | −27:48:30.6 | 92.29          | Faint neighbour   | 0.81 ± 0.24     | 0.90              | –                         |
| 30980    | 03:32:05.8 | −27:48:20.0 | 219.80         |                   | 0.49 ± 0.03     | −                 | –                         |
| 31343    | 03:32:42.9 | −27:48:09.4 | 32.93          |                   | 4.94 ± 0.82     | −                 | –                         |
| 32408    | 03:32:50.1 | −27:47:33.0 | 71.51          |                   | 0.25 ± 0.04     | −                 | –                         |
| 32940    | 03:32:34.4 | −27:46:59.6 | 120.10         |                   | 0.45 ± 0.04     | −                 | –                         |
| 32958    | 03:32:49.6 | −27:47:14.9 | 99.77          |                   | 0.54 ± 0.04     | −                 | –                         |
| 33160    | 03:32:04.9 | −27:46:47.3 | 613.60         |                   | 0.36 ± 0.03     | −                 | SF clumps                 |
| 33725    | 03:32:06.8 | −27:46:43.6 | 247.30         |                   | 0.56 ± 0.05     | −                 | –                         |
| 33872    | 03:32:21.1 | −27:46:44.0 | 26.93          |                   | 0.63 ± 0.06     | −                 | –                         |
| 34028a   | 03:32:11.8 | −27:46:28.0 | 155.10         |                   | 3.18 ± 0.19     | −                 | –                         |
| 34203a   | 03:32:38.0 | −27:46:26.4 | 93.26          | Faint neighbour   | 5.66 ± 2.72     | 0.42              | –                         |
| 34352    | 03:32:20.3 | −27:46:20.4 | 63.46          | Faint neighbour   | 0.74 ± 0.05     | −                 | –                         |
| 34640    | 03:32:54.6 | −27:46:06.3 | 83.87          |                   | 0.81 ± 0.08     | −                 | –                         |
| 36721    | 03:32:26.4 | −27:44:43.6 | 112.90         |                   | 1.45 ± 0.06     | −                 | –                         |
| 36935    | 03:32:23.1 | −27:44:42.1 | 66.15          |                   | 1.12 ± 0.06     | −                 | –                         |
| 39338    | 03:32:41.2 | −27:43:09.8 | 84.70          | Faint neighbour   | 0.83 ± 0.06     | −                 | –                         |
| 39669    | 03:32:04.6 | −27:43:00.6 | 189.90         |                   | 0.23 ± 0.06     | −                 | –                         |

#Supplementary information

a MUSYC catalogue ID, see Cardamone et al. (2010). Objects with X-ray detections are marked with *.

b See images shown in Fig. 1.

c The ratio of the host luminosity to the point source luminosity, reported only when GALFIT requires an unresolved object to yield a physical fit. This may be due to an AGN point source (in the case of the X-ray-detected DOGs) or an unresolved bulge or central concentration, i.e. a central bulge.

d See Fig. 2.
the residuals after subtracting the model fits for signs of mergers, dust lanes or spiral arms that emerge only in the subtracted image. We choose the F160W band as the reddest image available to map the stellar distribution. Particular care is taken to fix the background level to that computed by SExtractor to avoid confusing the background with disc light profiles. One object (25379) was too faint to fit at all, while another (27859) is very faint, though we were able to fit it. The obvious major merger, 29263, was fitted with separate Sérsic models for the two nuclei and another for the tidal tail. The fits to five of the objects required the addition of a point source due to the presence of a central concentration. This could either be a bulge or a faint point source in the case of the two X-ray-detected DOGs. Note that the HST WFC3/IR point spread function (PSF) shape is similar to that of a small bulge, so we cannot tell the two apart at high redshift. However, the physical size of the PSF full width at half-maximum (FWHM) corresponds to \( \sim 1 \) kpc, so in the case of an unresolved bulge, it is a minor component, and the whole galaxy is still disc dominated. The results of this fitting analysis are shown in Table 1 and examples are shown in Fig. 2.

We find that the majority of obscured quasar host galaxies have low Sérsic indices indicating a significant disc component to the rest-frame optical light profile. Following the simulations of Simmons & Urry (2008), the measured Sérsic indices mean that 23 are pure discs, three have significant discs and three are bulge dominated. We show the distribution of measured Sérsic indices in Fig. 3. Most of the residual images show very little leftover light after subtraction of the Sérsic model. None of them reveals previously undetected double nuclei. In the case of host galaxies with a clumpy appearance, notably 28086 and 33160, the more prominent, star-forming clumps remain visible in the residual; they feature characteristic blue colours. We conclude that the surface brightness fits agree with the visual inspection in finding a very low incidence of major mergers and no otherwise hidden mergers.

Finally, we verify that we are not missing bulges due to dust obscuration of bulge light (Gadotti, Baes & Falony 2010) by fitting a sample of star-forming galaxies with similar K-band magnitudes and redshifts as the DOGs and rest-frame \( U - V < 1.3 \) and \( V - J < 1.1 \) in order to select relatively dust-free galaxies and find that 14/15 are disc dominated \( n < 1.5 \) and one has some bulge \( (n = 2.61) \).

**Figure 2.** Four example images (left) and fit residuals (right). The top left highlights the second most disturbed object (28086) whose residual image shows a minor disturbance. The top right is a galaxy (29372) whose original image could feature either two nuclei, or a dust lane. The residual image does not reveal two nuclei, so it is most likely a dust lane. 33160 in the bottom left is an example of a disc with (blue) star-forming clumps that become more prominent after the subtraction of a very disc-like Sérsic model \( (n_{F160W} = 0.36 \pm 0.03) \). The bottom right is an example of a very clean subtraction of a disc-like Sérsic model \( n_{F160W} = 1.45 \pm 0.06 \), which does not reveal any hitherto invisible major merger signature such as double nuclei.

3.3 Could we miss major mergers?

The main caveat with this analysis is the question of whether features indicative of a major merger would be apparent given the quality of the data. We approach this question empirically by taking HST Advanced Camera for Surveys (ACS) I-band images of red quasars hosted by major mergers at \( z < 1 \) (Urrutia et al. 2008) and redshift them to \( z \sim 2 \), where the observed I band corresponds to the H band. We change the pixel scale and convolve the images with the WFC3/IR PSF of the CANDELS observations. We also increase the background to result in comparable signal-to-noise ratio. From this test, shown in Fig. 4, we find that the redshifted images lack some of the fine structure and faint tidal features but the major clumps and...
components that make up the major merger remain clearly visible as separate sources. This exercise shows that, while tidal tails and delicate disturbed features can disappear, the irregular, multicomponent nature of major mergers remains visible. We conclude that, were the DOGs major mergers like the red quasars, we would have been able to detect this.

3.4 Is the merger fraction luminosity-dependent?

The heavily obscured quasars studied here do not represent the most luminous quasars in the Universe. The most luminous quasars at all redshifts are red quasars, type 1 quasars reddened by dust (Glikman et al. 2012a,b). Observations of red quasars at moderate redshift (0.5 < z < 1) by Urrutia et al. (2008) show a very high fraction, close to 100 per cent, of major mergers. Future observations of even more luminous red quasars at z ~ 2 may well reveal similarly high levels of morphological disturbance. Observations of lower luminosity active galaxies, on the other hand, show very low levels of major merger activity (e.g. Cisternas et al. 2011; Schawinski et al. 2011; Kocevski et al. 2012). Given these observations, together with new analysis presented here, we suggest that the role of major mergers in triggering black hole growth is a function of the bolometric luminosity, with major mergers being the main channel only at the highest luminosities.

4 DISCUSSION

We have analysed deep HST WFC3/IR imaging of a sample of 28 DOGs at 1 < z < 3, ~90 per cent of which are expected to harbour a heavily obscured quasar whose IR and inferred bolometric luminosities are just below or around the break in the quasar luminosity function. The rest-frame optical host galaxy morphologies indicate that only one is unambiguously a major merger. Three additional objects may be undergoing some disturbance, but their appearance can be accounted for by star-forming clumps or dust lanes and another four objects have faint neighbours, which may or may not be associated. We further analyse the F160W images using GALFIT and verify that the residuals to the host galaxy fits do not reveal any hidden features or disturbances. Indeed, the host galaxies are smooth with low Sérsic indices, which means that the host galaxies are either disc-dominated system or have substantial discs. These results are consistent with observations by Bussmann et al. (2011).

We assume that the merger fraction of the heavily obscured quasars in our sample is representative of their less obscured and unobscured counterparts. As simulations predict that the heavily obscured phase coincides with the early, most disturbed ‘train wreck’ phase of the merger (e.g. Hopkins et al. 2006), it may in fact be a high estimate. These observational results challenge the picture in which quasar activity is triggered by major mergers. We find that the heavily obscured quasars studied here cannot be in the early- to mid-stages of a merger, as double nuclei and perhaps tidal tails would be apparent, as they are in one case. They also cannot represent the final stages of a merger, as 90 per cent have low Sérsic indices due to disc-dominated light profiles; the major merger should have disrupted the disc and built a spheroid by this stage. Simulations show that the merger remnants can re-grow a disc after some time (e.g. Robertson et al. 2006), though it requires extremely gas-rich mergers with particular initial orbits.

In summary, black hole growth in heavily obscured quasars near the break in the luminosity function at z ~ 2, the peak epoch of black hole growth, occurs predominantly in disc galaxies rather than in major ‘train wreck’ mergers. As the break in the luminosity function is where most black hole growth occurs, our result implies that secular processes, rather than major mergers, are the predominant driver of cosmic massive black hole growth.

ACKNOWLEDGMENTS

Support for the work of KS was provided by NASA through Einstein Postdoctoral Fellowship grant numbers PF9-00069, issued by the Chandra X-ray Observatory Center, which is operated by the SAO for and on behalf of NASA under contract NAS8-03060. BDS acknowledges support Yale University and from NASA grant HST-AR-12638.01-A. ET received partial support from CATA-BASAL (PB 06) and FONDECYT grant 1120061. This research has made use of NASA’s ADS Service.

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