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Are supermassive black holes shrouded by 'super-Oort' clouds of comets and asteroids?

Sergei Nayakshin,[1,2]★ Sergey Sazonov[3,2] and Rashid Sunyaev[2,3]

[1]*Department of Physics & Astronomy, University of Leicester, Leicester LE1 7RH*
[2]*Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, 85741 Garching bei München, Germany*
[3]*Space Research Institute, 117997 Moscow, Russia*

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ABSTRACT

The last decade has seen a dramatic confirmation that in situ star formation is possible inside the inner parsec of the Milky Way. Here we suggest that giant planets, solid terrestrial-like planets, comets and asteroids may also form in these environments, and that this may have observational implications for active galactic nuclei (AGN). Like in debris discs around main-sequence stars, collisions of large solid objects should initiate strong fragmentation cascades. The smallest particles in such a cascade – the microscopic dust – may provide a significant opacity. We put a number of observational and physical constraints on AGN obscuring tori resulting from such fragmentation cascades. We find that tori fed by fragmenting asteroids disappear at both low and high AGN luminosities. At high luminosities, $L \sim L_{\rm Edd}$, where $L_{\rm Edd}$ is the Eddington limit, the AGN radiation pressure blows out the microscopic dust too rapidly. At low luminosities, on the other hand, the AGN discs may avoid gravitational fragmentation into stars and solids. We also note that these fragmentation cascades may be responsible for astrophysically 'large' dust particles of $\gtrsim$µm sizes that were postulated by some authors to explain unusual absorption properties of the AGN tori.

Key words: accretion, accretion discs – Galaxy: centre – galaxies: active.

1 INTRODUCTION

Active galactic nuclei (AGN) are galactic centres powered by supermassive black holes (SMBHs) growing by accretion of gas. The specific angular momentum of gas in a galaxy is too large for it to be accreted on to the SMBH directly. An accretion disc (Shakura & Sunyaev 1973) is required to transfer the angular momentum outwards and mass inwards. The disc is massive and cool at large distances from the SMBH. For this very reason, AGN accretion discs are found to be gravitationally unstable and should collapse into stars beyond ∼0.01–0.1 pc (Paczyński 1978; Kolykhalov & Sunyaev 1980; Lin & Pringle 1987; Collin & Zahn 1999; Goodman 2003). The fragmentation process has been confirmed in numerical simulations (Nayakshin, Cuadra & Springel 2007; Alexander et al. 2008), and appears to be the only reasonable explanation for the two discs of young stars in the central ∼0.5 pc of our Galaxy (Genzel et al. 2003; Levin & Beloborodov 2003; Nayakshin & Cuadra 2005; Paumard et al. 2006).

Stars forming elsewhere in the Galaxy frequently, and perhaps always, form with planets and debris discs. In this paper we shall argue that stars forming in AGN discs should also come with their own planets, both giant and terrestrial-like, and should also have solid 'debris' around them – asteroids and comets. We show that planets and asteroids formed in the outer fringes of the protostellar disc around the parent star are stripped away by perturbations from close passages of stars in the AGN disc.

Released from their host stars, these solids and planets orbit the SMBH independently. Since the velocity kick required to unbind them from the host is in the km s^{-1} range, whereas the star's orbital velocity around the SMBH is $\gtrsim$1000 km s^{-1}, the orbits of the solids are initially only slightly different from that of their hosts. AGN gas discs are expected to be very geometrically thin (e.g. Nayakshin & Cuadra 2005), and if they always lie in the same plane (e.g. the disc galaxy's mid-plane) then the resulting distribution of solids will be quite thin and planar as well.

However, there is no particularly compelling reason for a single-plane mode of accretion in AGN, as the inner parsec is such a tiny region compared with the rest of the bulge (Nayakshin & King 2007), and chaotically oriented accretion may be much more likely (e.g. King & Pringle 2006). One physically plausible way to obtain randomly oriented inflows in AGN is turbulence, and, more generally, random motions, excited by the star formation feedback in the bulge of the host (cf. simulations of Hobbs et al. 2011).

Furthermore, there is one well-documented observational example of such a geometrically thick distribution of *stars* in the centre

★E-mail: sergei.nayakshin@astro.le.ac.uk

of our Galaxy. The two young stellar discs in the Galactic Centre are inclined to each other at a large angle, and the discs are possibly strongly warped (Bartko et al. 2009). While the nature and even the existence of the second disc are debated (Lu et al. 2009), it is plainly clear that the system of young stars in the centre of our Galaxy is very thick kinematically. A natural way to create such a complex distribution of stellar orbits is to have a violent collision of a giant molecular cloud (GMC) with another cloud or a pre-existing gas disc (Hobbs & Nayakshin 2009), or to have multiple GMC deposition events (Bonnell & Rice 2008; Alig et al. 2011).

In an AGN that is fed by repetitive randomly oriented 'feeding episodes', we expect many stellar rings forming over time at different angles to the galactic plane. The distribution of solids torn away from their parent stars should thus be similarly multi-plane. Due to the gravitational precession of different discs with respect to one another (Nayakshin et al. 2006), the system should evolve into a roughly quasi-spherical configuration or a thick torus if there is a preferred direction like the galactic plane. We refer to this torus of solid bodies as a super-Oort cloud of SMBHs due to an obvious analogy with the Solar system's Oort cloud (interestingly, the physical sizes of the two clouds would be roughly the same).

The total mass in the solids, compared to that in the gas or the stars within the inner parsec, should be tiny simply because H and He far outweigh metals in a gas of solar composition. Accordingly, we do not expect any significant effects of the solids on the dynamics of stars or gas in the central parsec. However, the smallest solids – microscopic dust particles – have very large absorption cross-section per unit mass and may be important for the observational appearance of AGN.

We now note an observational analogy. Dust around main-sequence stars absorbs the incident radiation and re-radiates it into the infrared (IR) and near-infrared (NIR) wavelengths. These dusty reservoirs around 'normal stars' are called debris discs because they are believed to be dominated by large (~100 km or so) solid bodies which are the remnants of the planet formation process. Debris discs around stars are optically thin (Wyatt 2008). Due to this, microscopic dust is continuously driven away by the radiation pressure from the star and thus needs to be replenished. The replenishment occurs via a top-down cascade of larger solid bodies colliding and fragmenting on ever smaller objects. This general picture is supported by observations of such collisional cascades in our own Solar system, in the Kuiper and in the asteroid belts. Some of the debris discs around nearby stars have been directly imaged (e.g. Smith et al. 2009).

The relative velocities of solids in the super-Oort cloud around SMBHs envisaged here are as large as hundreds to thousands of km s^{-1}, compared with $\lesssim$ km s^{-1} for debris discs around stars in the solar neighbourhood. This should fuel a powerful fragmentation cascade that may in principle lead to an optically thick veil of dust, perhaps contributing to the observed but still poorly understood AGN obscuration (cf. Section 4.1 for literature on this). On the other hand, dust particles could be quickly blown away, could collapse into a geometrically thin disc, or be sublimated by the AGN radiation; the cascade may also become depleted 'too soon'.

The purpose of our paper is to put physical constraints on the fragmentation cascade of solid bodies, such as asteroids and comets, around a SMBH to determine its observational significance for the AGN phenomenon. We start in Section 2 with arguments for the feasibility of planet formation near AGN. In Section 3 we estimate time-scales for catastrophic collisions of large bodies feeding the cascade to smaller scales, and in Section 4 observations of AGN obscuration are used to constrain the population of small ~μm sized grains. To simplify the estimates, we assume that large solid bodies (comets, asteroids and Moon-sized objects) dominate the mass in the fragmentation cascade, whereas the small grains provide all the opacity (obscuration). In Section 5 a general discussion of the constraints on and the implications of our model is given. We note that our work does not exclude the 'conventional' gas-rich torus models for AGN tori (see the references in Section 4.1). It is possible that AGN obscuration is achieved by a variety of means in different sources or at different epochs of AGN evolution.

2 PLANETS, COMETS AND ASTEROIDS NEAR A SMBH

2.1 Birth of planets

Can planets and/or asteroids form in the protoplanetary discs around their parent stars that orbit a SMBH at velocities as large as ~1000 km s^{-1}? The theory of planet formation is in itself an active area of research with widely differing opinions on how the process works, thus the answer to the question is model-dependent. Nevertheless, we shall argue that the answer to the above question is probably 'yes'.

One physical constraint on the planet formation process around a star in the AGN environment is that the required protoplanetary disc must fit within the Hill radius, $R_{\rm H}$, of the parent star, or else the disc would be truncated by the tidal forces from the SMBH. For a parent star with mass $M_* = 1\,{\rm M}_\odot$, orbiting a black hole of mass $M_{\rm bh} = 10^8\,{\rm M}_\odot\,M_8$, a distance R away, Hill radius is

$$R_{\rm H} = R\left(\frac{M_*}{3\,M_{\rm bh}}\right)^{1/3} = 300\ {\rm au}\ R_{\rm pc} M_8^{-1/3}\ , \qquad (1)$$

where $R_{\rm pc} = R/(1\,{\rm pc})$. For solids formed closer than ~100 au to their host stars, this constraint is satisfied unless $R_{\rm pc} \ll 1$.

2.1.1 Core accretion

The earliest versions of the core accretion (CA) model for planet formation were based on observations of the Solar system only (e.g. Safronov 1972), and suggested a rather slow formation of terrestrial planets from 'planetesimals', e.g. solid bodies with sizes of a few km (for a review see Wetherill 1990). Solids of these comparatively small sizes have surface escape velocities of the order of $\sim$ m s^{-1}. Collisions at velocities exceeding that would be shattering, therefore the initial growth is assumed to occur in razor-thin discs with very small velocity dispersions. This mode of rocky planet formation would not be able to build any large solid bodies near an AGN due to the rapid collisional destruction of such bodies in collisions at ~1000 km s^{-1} (cf. equation 8). In other words, even if the planetesimals were born in the protoplanetary discs near the stars, no large solid objects would be able to grow from them and the planetesimals would be very quickly destroyed themselves in fragmenting collisions.

However, more recent work indicates that a more rapid planetesimal growth may happen due to turbulence and instabilities in the gas–dust disc (e.g. Youdin & Goodman 2005; Johansen et al. 2007). In these models, small rocks are first concentrated into regions shaped by the motions of the gas flow around them, and then undergo a gravitational collapse to form larger solids. Numerical simulations suggest that growth of solids up to minor planet sizes may occur as rapidly as within $\sim 10^3$–10^4 yr in this setting (Johansen et al. 2007). It appears that this mode of planetesimal and rocky core

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formation may be resilient enough to the tidal and radiation field challenges of the central parsec of galactic nuclei.

2.1.2 Gravitational disc fragmentation

Observational evidence is accumulating for planets that probably did not form according to the CA scenario. The giant planets observed at many tens and hundreds of au from their parent stars [see references and discussion in Boley (2009) and Murray-Clay (2010)] could not have their cores assembled on reasonably short time-scales (Rafikov 2011). Therefore, these planets are believed to have formed by the gravitational disc instability (GI) in the outer fringes of protostellar accretion discs (Mayer et al. 2004; Rice, Lodato & Armitage 2005; Durisen et al. 2007; Stamatellos & Whitworth 2008; Boley 2009). This is a miniature version of the star formation process near an AGN, with planets born around individual stars.

An important modification of the GI theory allows the formation of terrestrial-like planets and all sorts of smaller solids such as the asteroids, breaking the quarter-century-held belief that rocky planets can be only formed by CA. Boley et al. (2010) and Nayakshin (2010a) have recently showed that radial migration of protogiant planets may pave the way to the formation of terrestrial planets. In these models, which we call here 'tidal downsizing' (TD), a 'large' $R_{\rm disc} \sim 100$ au gas–dust disc fragments in to many self-gravitating clumps. These clumps migrate inwards rapidly. Dust grains within the clumps grow and move to the centre of the clumps to form massive solid cores – the prototerrestrial planets. The gaseous envelopes of the clumps may be removed by the tides from the parent star or by stellar irradiation, and later accreted on to the star. Only the solid core (the future rocky protoplanet) is left behind as its material density is far higher than that of the gaseous embryo. Rotation, not taken into account in this simplest picture, prevents segregation of all of the solid material in the centre, and may lead to the formation of planetary satellites such as the Moon (Nayakshin 2011a), and other smaller solid debris. Disruption of the gaseous envelope then releases the solid debris into the surroundings [cf. figs 9 and 10 in Cha & Nayakshin (2011), for small grains disrupted together with the gas; Cha & Nayakshin, (in preparation) show that large asteroids are also unbound from protoplanet except for those inside its Hill radius].

The formation of solid bodies in the TD framework is a very rapid process, taking $\sim 10^3$–10^4 yr (Nayakshin 2010b, 2011b; Cha & Nayakshin 2011). Thus solids would be in place as rapidly as the star formation starts in the AGN disc in this model.

2.1.3 Starless planets in AGN discs

Shlosman & Begelman (1989) noted that not only stars but also giant gas planets can be born directly in AGN discs (not around individual stars). Similarly, Nayakshin (2006) found that the Toomre mass of the marginally self-gravitationally unstable disc may permit the formation of objects in the planetary mass regime (cf. his fig. 1), although the final outcome of disc gravitational fragmentation depends on whether the massive planets/stars accrete more mass or not.

It is now understood that planets formed by the GI can hatch solid cores (Boss 1998; Boley et al. 2010; Nayakshin 2011b). If these are then stripped of their gas envelope by tidal forces, irradiation, passages through the disc (as argued for stars by Goodman & Tan 2004) or close interactions, then these cores are also liable to participate in the collisional fragmentation cascade discussed below, provided that the impactors are large enough.

2.2 Decoupling from the parent star

As in the case of the Oort cloud in the Solar system, one can expect that smaller solids such as asteroids formed in the protoplanetary disc are scattered by planets on to larger orbits, and some are lost from the Hill sphere of the parent star altogether (cf. references in Fernandez 1997). Besides the Oort cloud itself, the most convincing evidence for the importance of this process comes from observations of 'freely floating' giant planets (Sumi et al. 2011) that may number as many as two per main-sequence star in the Milky Way. These planets were probably expelled from their parent systems by close encounters with even more massive bodies. Anything less massive than a giant planet would be even more likely to suffer a similar fate then.

Close passages of stars can also strip away solid bodies in the outer reaches of the system. In the impulse approximation, the momentum passed to a solid body by a star passing with a relative velocity $v_{\rm rel}$ scales as $\propto v_{\rm rel}^{-1}$ (cf. section 1.2.1 of Binney & Tremaine 2008). Therefore, only encounters with small relative velocities are important in stripping the solids from the parent stars. During the birth of the stars and planets in the AGN accretion disc, the relative velocity is expected to be $\sim(H/R)v_K \lesssim$ tens of km s^{-1} (Nayakshin & Cuadra 2005). Consulting fig. 2 of Zakamska & Tremaine (2004), we see that solids in the outer (tens of au) part of the disc should be stripped by just a few stellar passages within a few hundred au of the parent star. Such passages are frequent inside the AGN star-forming discs. Indeed, the gas disc vertical scaleheight is expected to be $H \sim 0.01R = 200$ au at $R = 0.1$ pc (Nayakshin & Cuadra 2005). The mean stellar separations may be expected to be of the order of H (cf. related estimates for gas clump–clump collisions in Levin 2007).

We therefore conclude that solids born in the gas–dust discs in the outermost $\sim$ tens of au from their parent stars are vulnerable to external perturbations releasing them into independent orbits around the SMBH. Solids born in the inner 10 or so au are much harder to perturb out of the grips of their host stars. These are more likely to be excited on to eccentric orbits within the Hill radius of the star. However, these star-bound solids do participate in the global fragmentation cascade as they are hit by 'external' solids at the same rate as solids on their own independent orbits. Therefore, within our approximate exploratory model, we can consider both populations in the same manner.

3 FRAGMENTATION CASCADE

The problem we wish to study is not amenable to an exact analytic study. Our goal here is to place order of magnitude constraints on the picture being proposed, keeping the arguments as transparent as possible. In the context of fragmenting asteroids and debris discs around stars, one frequently assumes a quasi-steady-state fragmentation cascade of solids to form (Dohnanyi 1969; Wyatt 2008). In this case solids of a given size a are removed by fragmentation at the same rate as solids of the same size arrive due to the fragmentation of larger bodies.

For the problem at hand, such a steady state might exist at intermediate sizes only because the smallest grains are strongly affected by aerodynamic gas drag, whereas the largest objects may not have had enough time to experience a catastrophic (shattering) collision.

Therefore, we chose to consider two populations of solids separately. The largest solids have diameter D and dominate the system in terms of mass. The rate of their fragmentation determines the rate of dust production. The small grains considered in Section 4.2, e.g. the dust, dominate the absorption opacity of the system.

3.1 Fragmentation of large bodies

Consider large solids in Keplerian orbits around the SMBH with semimajor axis $\sim R$ and number density $n_{\rm D}$. One can estimate the self-collision time-scale for these large solids immediately, and that is likely to be quite long. However, every one such collision may create thousands and millions of smaller objects. Many of these fragments may be large enough to split the large bodies (see equation 4). Furthermore, it is not realistic to assume that no small bodies are born during star and planet formation in AGN discs (cf. the arguments at the end of this section).

Therefore, we shall estimate the time-scale on which the large bodies D are destroyed differently. We assume that one way or another, a fragmentation cascade develops. We take a power-law form for the cascade with $\Delta n_d = n_D^0 (d/D)^{-q} \Delta d$ giving the number density of asteroids with diameter between d and $d + \Delta d$. Steady-state fragmentation cascades result in $3.5 \le q \le 4$ (Dohnanyi 1969; Kennedy & Wyatt 2011). We estimate the number of asteroids of size d as

$$n_d \sim d \left(\frac{\Delta n_d}{\Delta d} \right) \sim n_D (d/D)^{-i} , \quad (2)$$

where $i = q - 1$ and $n_D = n_D^0 / D$.

The rate at which solids are ground is determined by catastrophic collisions, e.g. collisions resulting in fragmentation of the larger body. The size d of the impactor in a catastrophic collision is determined from the condition that its kinetic energy relative to the asteroid D is equal to the binding energy of the latter, $\sim G[(\pi/6)\rho_a D^3]^2/D$. The relative velocity of the solids before the collision is

$$v_{\rm rel} = \delta v_K \approx 1000 \text{ km s}^{-1} \; \delta M_8 R_{\rm pc}^{-1/2} , \quad (3)$$

where $\delta \lesssim 1$ is a dimensionless parameter. This velocity is clearly far higher than the range of collision velocities studied in the context of asteroids around stars in a 'normal' Galactic environment.

The minimum size of the impactor that would split an asteroid of diameter D is

$$d = \left(\frac{\pi G \rho_a}{3 v_{\rm rel}^2} \right)^{1/3} D^{5/3} . \quad (4)$$

Numerically,

$$\frac{d}{D} \approx 4.6 \times 10^{-3} D_8^{2/3} v_8^{-2/3} , \quad (5)$$

where $D_8 = D/1000$ km and v_8 is $v_{\rm rel}$ in units of 1000 km s^{-1}. This shows that a 1000 km sized asteroid can be split by a projectile of only $\sim$5 km across if the impact occurs at $v_{\rm rel} \sim 1000$ km s^{-1}.

The catastrophic collision time-scale can be estimated as $t_{\rm coll} = [n_d v_{\rm rel} \pi (D/2)^2]^{-1}$ which results in

$$t_{\rm coll} \approx (G\rho_a)^{i/3} \, n_D^{-1} v_{\rm rel}^{-2i/3-1} D^{5i/3-2} . \quad (6)$$

In order to constrain this further, let us relate n_D to the total mass of solids, M_Z, occupying volume $\sim(2\pi/3)R^3$ (i.e. half of the spherical volume of radius R as seen from the SMBH). As the mass of one asteroid is $(\pi/6)\rho_a D^3$, we have $n_D = (3/\pi)^2 M_Z/(\rho_a D^3 R^3) \sim M_Z/(\rho_a D^3 R^3)$. Hence we estimate

$$t_{\rm coll} \approx \rho_a^{i/3+1} G^{-1/2} R^{i/3+7/2} D^{2i/3+1} M_Z^{-1} \, M_{\rm bh}{}^{-i/3-1/2} . \quad (7)$$

For $\rho_a = 2$ g cm^{-3} and $i = 2.5$,

$$t_{\rm coll} \approx 5 \times 10^6 \text{ yr } R_{\rm pc}^{13/3} D_8^{8/3} M_{Z3}^{-1} M_8^{-4/3} . \quad (8)$$

Here $M_{Z3} = M_Z/10^3 \, {\rm M}_\odot$. For reference, setting $i = 3$ results in $t_{\rm coll} \approx 0.4$ Myr for the same nominal parameters as above.

Equation (8) demonstrates that very large solid bodies, e.g. of a planetary satellite size, such as the Moon, are able to feed the cascade for interestingly long time-scales. Bodies of smaller sizes would be ground down too quickly to be observationally important as such fragmentation cascades would be optically thin.

'Primordial' solid formation (e.g. concurrent with the star formation itself) in normal Galactic conditions creates a distribution of solid bodies which is currently not well known (see Shannon & Wu 2011). Consider now the modifications to our picture resulting from the large bodies themselves having a range of sizes rather than a fixed size. Because the collision time is a very strong function of the asteroid size D, equation (8) shows that smaller bodies will be shattered very quickly. In contrast, the largest bodies, e.g. of the size of the Earth, are fragmented on very long time-scales (10^9 yr or more). At any given time t, counted from the last star and planet formation event, the fragmentation cascade is fed by asteroids of size $D(t)$ such that $t_{\rm coll}(D) = t$. Most of the asteroids larger than $D(t)$ have not yet had time to fragment by the time t. M_Z in this case should be understood as the mass of the asteroids with diameter $D = D(t)$.

4 AGN ABSORBERS AND SMALL GRAINS IN THE SUPER-OORT CLOUDS

As stated in the Introduction, in this paper we explore whether AGN absorbers may be more massive cousins of stellar debris discs, made up of solids from $\sim$ millions of debris discs around individual stars. Having discussed the fragmentation cascade of the largest solids, we now assume that the end result of this is a population of dust particles able to absorb and re-radiate the AGN radiation. In the spirit of an exploratory model, the population of the smallest grains is described by grains of a single radius, a, which is taken to be of μm size. We refer to these grains as 'small' in comparison to the larger solid bodies we consider, even though they may be somewhat large by the standards of Galactic grains, where $a \lesssim 0.25$ μm (Mathis, Rumpl & Nordsieck 1977). As for debris discs (Wyatt 2008), we assume that the small grains completely dominate the opacity of the absorber, whereas the mass is dominated by the large bodies.

4.1 Observations and models of AGN absorbers

According to the unified model of AGN, the central source has fundamentally the same properties in the two types of AGN (e.g. Antonucci & Miller 1985; Antonucci 1993; Urry & Padovani 1995). It is only because of an obscuring medium, presumed to be a geometrically thick torus, that the type 1 and the type 2 AGN differ. In type 2 AGN, the torus is assumed to be oriented edge-on to the observer to block the view towards the SMBH. In type 1 AGN, on the other hand, the torus is oriented face-on, allowing a direct view of the source. Observationally, there is plenty of robust evidence confirming this simple geometrical model at frequencies ranging from the IR to hard X-rays (Antonucci & Miller 1985; Maiolino & Rieke 1995; Urry & Padovani 1995; Bassani et al. 1999; Risaliti, Maiolino & Salvati 1999; Lutz et al. 2004; Heckman et al. 2005; Buchanan et al. 2006; Meléndez et al. 2008).

The optical/UV luminosity of AGN is absorbed in the torus by the dust grains and is re-radiated at IR and NIR frequencies (e.g.

Rees et al. 1969; Edelson & Malkan 1986; Barvainis 1987; Pier & Krolik 1992; Laor & Draine 1993). This bright IR emission has been studied with interferometry in recent years (e.g. Jaffe et al. 2004; Packham et al. 2005; Prieto, Maciejewski & Reunanen 2005) allowing one to estimate the physical sizes of the tori. These turn out to be rather small, ranging from ~0.03 to 1 pc at NIR (e.g. Kishimoto et al. 2011) frequencies, to 1 pc to tens of parsecs at 12 μm (Tristram et al. 2009; Tristram & Schartmann 2011).

Despite all the solid evidence for the existence of tori, no convincing theoretical model has been ever produced to explain the torus properties. The underlying theoretical difficulty is the following. To harbour dust, gas needs to be no hotter than ~2000 K. The sound speed of such gas is only $\sim 1\,\mathrm{km\,s^{-1}}$, whereas the vertical extent of the torus requires sound velocities of at least a few hundred km $\mathrm{s^{-1}}$. The torus could also be made of cool clouds with large random velocities supporting the torus against collapse. However, in order to provide a large enough absorbing column depth, there should be $N_{\rm los} \sim$ several to 10 clouds on a typical line of sight. But this also means that these clouds collide $\sim 2\pi N_{\rm los} \gg 1$ times per orbit (Krolik & Begelman 1986, 1988). How Mach number $\gtrsim$100 collisions do not destroy the gas clouds completely in a fraction of a period, given their frequent collisions, appears to be beyond common sense [to solve this dilemma, Krolik & Begelman (1986) proposed the clouds to be very strongly magnetized].

Having said this, we note that a single universal model for AGN obscuration may not even exist as the dominant absorption mechanism may vary from source to source and even in time in the same source (Risaliti, Elvis & Nicastro 2002). Examples of processes likely to provide obscuration in AGN are: winds driven by a variety of processes (e.g. Königl & Kartje 1994; Kartje, Königl & Elitzur 1999; Elvis 2000; Proga 2003; Elvis et al. 2004; Elitzur & Shlosman 2006; Nayakshin & Cuadra 2007), warped accretion discs (Nayakshin 2005), a clumpy medium produced by star formation (Wada & Norman 2002; Schartmann et al. 2010), infrared radiation supported tori (Krolik 2007), temporary obscuration events produced by broad line region (BLR) clouds perhaps in a cometary shape (Maiolino et al. 2010), and of course obscuration by larger scale structures (the dust lanes, etc.) in the host galaxy.

4.2 Constraints on the smaller grains

We now consider constraints on the population of the smallest grains of a single radius, a.

4.2.1 Absorption by the grains in the optical

The absorption cross-section, $\sigma_{\rm abs}$, for grains with size a larger than 0.1–1 μm (depending on grain composition; see figs 2–4 in Laor & Draine 1993) is approximately equal to their geometric area, πa^2 at wavelengths from optical to soft X-rays ($h\nu \lesssim 1$ keV). Within our order of magnitude treatment, this provides a sufficiently accurate prescription.

Let the number density of grains inside the absorber be n_a. The number of grains on a line of sight is

$$N_a = n_a \pi a^2 R, \tag{9}$$

where R is the radial thickness of the torus, which we consider to be of the order of the distance to the SMBH. We note that $N_a \gg 1$ or else, due to Poisson statistics, a sizable fraction of the lines of sight would contain no dust grains at all. This would contradict the strong absorption of the broad lines in type 2 AGN (Antonucci & Miller 1985).

4.2.2 Constraints from X-ray frequencies

Individual grains with size $a < a_0 \lesssim 1000$ μm are optically thin to X-rays with energy of a few keV (X-rays with this characteristic energy typically determine the absorption column depth in observations). Therefore, in contrast to optical frequencies, absorption of the primary AGN continuum in X-rays measures the total column depth of the grains on the line of sight. This column depth can be related to the total mass of the small grains for a given size of the torus. If the volume of the torus is $V_{\rm t} \approx 2\pi R^3/3$, then the total mass of the grains in the torus is

$$M_a = \frac{2\pi R^3}{3} n_a \rho_a \frac{4\pi}{3} a^3 \,, \tag{10}$$

where ρ_a is the material density of a grain. The column depth of the grains on a line of sight is

$$\Sigma_a = n_a R \frac{4\pi}{3} \rho_a a^3 \,. \tag{11}$$

The required surface density of metals in AGN absorbers can be deduced from the 'hydrogen column' $N_{\rm H}$ reported in X-ray surveys (e.g. Sazonov & Revnivtsev 2004; Guainazzi, Matt & Perola 2005; Sazonov et al. 2007). These assume that the metal-to-gas mass ratio is $\zeta_{\rm met} = 0.02$ as appropriate for gas of solar composition. Our model then ought to satisfy $\Sigma_a = \zeta_{\rm met} N_{\rm H} m_{\rm H}$, where $m_{\rm H}$ is the mass of a hydrogen atom. This gives a constraint on the product

$$a N_a = \frac{3\zeta_{\rm met} N_{\rm H} m_{\rm H}}{4\rho_a} \approx 10^{-3} N_{23} \,, \tag{12}$$

in cm, where we set $\rho_a = 2\,\mathrm{g\,cm^{-3}}$ and $N_{\rm H} = N_{23} 10^{23}\,\mathrm{cm^{-2}}$. The total mass of the grains (equation 10), required to fulfil the X-ray constraints, becomes

$$M_a = \frac{2\pi}{3} R^2 \zeta_{\rm met} N_{\rm H} m_{\rm H} = 300\,\mathrm{M_\odot}\; R_{\rm pc}^2 N_{23}. \tag{13}$$

For a given number of grains on the line of sight, N_a, the grain size can be estimated as

$$a = 10\,\mu\mathrm{m}\; N_{23} N_a^{-1} \,. \tag{14}$$

Note that if $N_a \gg 1$ then $a \lesssim 1$ μm for $N_{23} = 1$.

4.2.3 The role of gas

In contrast to debris disc systems where gas is presumed to be absent (Wyatt 2008), the AGN tori cannot be totally devoid of gas because the AGN is fed by accretion of gas. We can estimate the minimum column density of gas in the torus, $\Sigma_{\rm g} = \rho R$, where ρ is the gas density in the torus, via the mass continuity for gas accreting through the torus:

$$\Sigma_{\rm g} \sim \frac{\dot{M}}{2\pi R v_{\rm ff}} = 5 \times 10^{-4}\,\mathrm{g\,cm^{-2}}\; \dot{M}_{-2} R_{\rm pc}^{-1/2} M_8^{-1/2} \,, \tag{15}$$

where $\dot{M}_{-2} = \dot{M}/(0.01\,\mathrm{M_\odot\,yr^{-1}})$ is the dimensionless gas accretion rate on to the AGN, $R_{\rm pc} = R/(1\,\mathrm{pc})$, and $v_{\rm ff} = (2GM_{\rm bh}/R)^{1/2} = 2^{1/2} v_K$ is the free-fall velocity.

The aerodynamic drag force on the grains due to the presence of gas is likely to be significant. For supersonic grain speeds, v, the drag force is $F_{\rm d} \approx (1/2)\pi a^2 \rho v^2$ (Wegener & Ashkenas 1961). The stopping time of the grain, $t_{\rm s} = (4\pi/3)\rho_a a^3 v/F_{\rm d}$. Comparing this to the dynamical time, $t_{\rm dyn} = R/v_K$, we have $t_{\rm s}/t_{\rm dyn} = (8/3)a\rho_a/\Sigma_{\rm g}$. Thus grains of μm size will be stopped by the aerodynamic friction in a dynamical time even at the minimum $\Sigma_{\rm g}$ calculated above.

Grains of ∼cm sizes will be strongly affected by the gas after a sufficiently long time.

This demonstrates that small grains that are crucial to the obscuration schemes of AGN are 'frozen in' with the gas. Therefore, the issue of the vertical pressure support for the torus must be addressed in this model even if the origin of the small grains is a vertically extended collisional cascade.

4.2.4 *Radiation pressure from the AGN*

Radiation pressure of the AGN can blow the grains away if the bolometric luminosity, $L_{\rm bol} = l_{\rm bol} L_{\rm Edd}$, is large enough. Here $L_{\rm Edd} = 4\pi G M_{\rm bh} c/\kappa_{\rm e}$ is the Eddington luminosity of the black hole, and $\kappa_{\rm e}$ is the electron scattering opacity. In the case of an optically thin torus, Laor & Draine (1993) find that grains smaller than

$$a_{\rm b} \approx 6 \times 10^3 \mu{\rm m}\; l_{\rm bol} \tag{16}$$

are blown out by the radiation field. Clearly, except for very dim sources where $l_{\rm bol} < 10^{-4}$, μm sized grains are expected to be driven out quickly if the torus is optically thin.

However, the absorber in which we are interested is optically thick to most of the AGN radiation (dominated by the UV bump). We expect the radiation pressure incident on the AGN-facing side of the absorber to be $\sim L_{\rm bol}/2c$, where 1/2 comes from the fact that roughly half of the AGN radiation is intersected by the torus. This factor should be reduced further if AGN radiation is beamed in the direction perpendicular to the absorber's symmetry plane. The absorber's weight is $G M_{\rm bh} M_{\rm t}/R^2$, where $M_{\rm t}$ is the total torus mass, consisting of the small grains mass, M_a, and the gas mass, $M_{\rm g}$. Requiring that the torus weight is greater than the radiation pressure on it, we find that

$$M_{\rm t} > 2\pi R^2 l_{\rm bol} \kappa_{\rm e}^{-1} \approx 10^3\, {\rm M}_{\odot} l_{-2} R_{\rm pc}^2 \;, \tag{17}$$

where $l_{-2} = l_{\rm bol}/0.01$. Since $M_a = (8\pi/9) R^2 \rho_a a N_a$, we get a radius-independent constraint on the product aN_a:

$$a N_a > \frac{9 M_a}{4\kappa_{\rm e} \rho_a M_{\rm t}} l_{\rm bol} \approx 3 l_{\rm bol} \frac{M_a}{M_{\rm t}} = 3 l_{\rm bol} f_{\rm d} \;, \tag{18}$$

where we have introduced the dust mass fraction in the torus, $f_{\rm d} \equiv M_a/(M_{\rm g} + M_a)$, for brevity. If the torus is composed of gas with the usual dust-to-gas abundance then $f_{\rm d} = 0.01$. If the torus is dust free, like a classical debris disc around a star, then $f_{\rm d} = 1$.

Interestingly, equation (12) now requires that the hydrogen column depth of the absorber exceeds

$$N_{23} > 30 f_{\rm d}\, l_{-2} \;. \tag{19}$$

This equation shows that, even for the normal dust-to-gas mass ratio of $f_{\rm d} = 0.01$, *static* AGN tori would have to be Compton-thick ($N_{23} > 10$) in bright Eddington-limited quasars, for which $l_{-2} \sim 100$. Static Compton-thin tori are not feasible for quasars: Compton-thin tori must be in the state of an outflow driven by the quasar's radiation pressure.

4.2.5 *Internal pressure support for grains*

We shall now argue that radiation released in the torus internally by accretion of gas through an accretion disc or by the stars may be sufficient to inflate the torus vertically. This aspect of our model is therefore similar to the model of Krolik (2007) and Shi & Krolik (2008), and is also related to the larger scale disc models of Thompson, Quataert & Murray (2005). The radiation pressure in the middle of the torus can be estimated as

$$P_{\rm rad} \sim \tau_{\rm t} \frac{F_{\rm t}}{c} \;, \tag{20}$$

where $F_{\rm t}$ is the radiation flux emerging from the torus due to the internal energy liberation, and $\tau_{\rm t} = \kappa_a \Sigma_a \gg 1$ is the optical depth of the torus. We assume that grains are sufficiently large to be in the geometric optics absorption regime for the infrared radiation of the torus as well, so that $\kappa_a = (\pi a^2)/(4\pi \rho_a a^3/3) = 3/(4\rho_a a)$. As the torus vertical scaleheight is about its radius, the pressure balance in the vertical direction reads $P_{\rm rad} \simeq (G M_{\rm bh}/2R^2)\Sigma_{\rm t}$. Thus, $F_{\rm t} \simeq (G M_{\rm bh} c/2\kappa_a R^2) f_{\rm d}^{-1}$. Given that the absorber's surface area is $\sim 2\pi R^2$, the internal radiation flux can be converted into the luminosity of the torus generated internally:

$$\frac{L_{\rm t}}{L_{\rm Edd}} \simeq \frac{\kappa_{\rm e}}{4 f_{\rm d} \kappa_a} \approx 5 \times 10^{-6}\; f_{\rm d}^{-1}\; a_{\mu{\rm m}} \;, \tag{21}$$

where $a_{\mu{\rm m}} = a/(1\;\mu{\rm m})$.

This estimate gives the internal luminosity of the torus needed to provide the vertical pressure support. Is this a reasonable luminosity to be expected from stars within the torus? To answer this, we assume that the luminosity of the stellar population with mass M_* is dominated by young massive stars (anticipating that AGN activity and star formation in the central parsec go hand in hand). Integrating over the standard stellar mass function, we get $L_* \approx 0.002(4\pi G c M_*/\kappa_{\rm e})$, where M_* is the total mass of the young stars. The expression in the brackets is the Eddington luminosity for mass M_*. If the mass function of stars is top-heavy, as in the Galactic Centre star formation event inside the central parsec (Nayakshin & Sunyaev 2005; Paumard et al. 2006; Bartko et al. 2010), the luminosity per unit mass can be higher, which we parametrize by introducing a dimensionless factor ϵ_* which is greater than unity for a top-heavy IMF. Therefore, to satisfy equation (21), the total mass of young stars inside the absorber must equal

$$M_* \approx 0.005\, M_{\rm bh}\, \frac{1}{f_{\rm d}\epsilon_*}\, a_{\mu{\rm m}} \;. \tag{22}$$

Unless $f_{\rm d}\epsilon_* \ll 1$, this number does not appear to be excessively large: it is comparable to the gaseous mass of a marginally unstable AGN accretion disc (Nayakshin & Cuadra 2005) that is needed to initiate star formation in an AGN disc. Finally, for reference we note that for a stellar population composed of Sun-like stars only, $\epsilon_* \approx 0.02$, whereas for an extremely top-heavy IMF, ϵ_* can be as large as ≈500.

4.2.6 *The inner edge of the torus*

Dust grains heated by the AGN to temperatures greater than ∼1000 K are sublimated. The effective temperature of the radiation from an AGN with luminosity $L_{\rm bol}$ a distance R away is found from $T_{\rm eff}^4 \approx L/(4\pi R^2 \sigma_B)$. This defines the inner edge to any dust-dominated torus,

$$R_{\rm pc} \approx T_3^{-2} l_{\rm bol}^{1/2} M_8^{1/2} \;, \tag{23}$$

where $T_3 = T_{\rm eff}/10^3$ K is the grain sublimation temperature in units of 10^3 K. We have glossed over the fact that different species of dust and different size dust can be sublimated at slightly different temperatures (e.g. Laor & Draine 1993).

4.3 Summary of observational constraints

Large solids feeding the cascade can be said to be 'adiabatically' collisionless, e.g. not likely to suffer a serious collision in a dynamical time (equation 8). This is an attractive feature of our model: large asteroids can remain in a kinematically and geometrically thick distribution for astrophysically interesting times, as required by AGN obscuration models (Antonucci & Miller 1985; Krolik & Begelman 1986, 1988).

However, the small grains are strongly influenced by even modest amounts of gas present in the torus (Section 4.2.3). Further, if small grains form an optically thick system they should also be collisional if moving at large random velocities [the arguments of Krolik & Begelman (1986), apply in this case to the individual dust grains]. The upshot of this is that the small grains should settle dynamically to a symmetry plane (which may be in general warped). Therefore, radiation pressure support internal to the torus is still needed to keep the torus geometrically thick.

On the other hand, the observed obscuration at optical and X-ray frequencies inside the AGN absorbers gave us a minimum column depth in the grains that the screen of small grains needs to possess in order to account for the absorption. This translates into the total mass of the grains if the size of the torus is known (see equation 13). The size of the torus is a fraction of a parsec based on both interferometric observations and the dust sublimation constraints (equation 23).

We then assumed that the radiation pressure support comes from the same stars that formed the dust, and estimated the total mass in the stars in equation (22). We can now close the logical loop by checking if these stars could actually provide the solids needed to fuel the cascade in the first place.

Take the ratio of the torus mass in the grains, obtained by using X-ray constraints (equation 13), to that of the stars needed for the pressure support:

$$\frac{M_a}{M_*} = 5 \times 10^{-4} \frac{R_{\rm pc}^2 N_{23}}{M_8\, a_{\mu\rm m}}\, \epsilon_* f_{\rm d}\, . \qquad (24)$$

Now, we can eliminate $R_{\rm pc}$ from this equation by assuming that the torus is larger than the dust sublimation radius given by equation (23). Finally, in order for the smallest grains to withstand the radiation pressure from the AGN, we require a minimum column depth N_{23} in equation (19). We now use that in equation (24) and find that the ratio of the mass in the small grains to that of the stars should satisfy

$$\frac{M_a}{M_*} > 1.5 \times 10^{-6} \frac{\epsilon_* l_{-2}^2 f_{-1}^2}{a_{\mu\rm m} T_3^4}\, , \qquad (25)$$

where $f_{-1} = f_{\rm d}/0.1$. This is a significant constraint on our model. It delineates the regimes where the fragmentation cascades may or may not be important for the observed AGN obscuration.

The realistically available budget of solids has an obvious upper limit – the total mass of metals with respect to that of H and He, i.e. $M_a/M_* < M_Z/M_* \sim 0.01$. This is of course wildly optimistic. To do better than that, consider observations of planetary systems and their debris discs. In the Solar system, most of the solid mass, outside of the Sun, is in the solid cores of the giant planets. That amounts to $\sim$50–60 $M_{\oplus}$, which gives a fraction $M_Z/M_{\odot} \approx 1.5 \times 10^{-4}$ of the total system's mass. Protoplanetary discs, before turning into debris discs, are found to contain up to a few to 10 times more mass in the dust than this (e.g. see fig. 3 in Wyatt 2008). Therefore, even being optimistic, it is hard to expect that solids in asteroids, terrestrial-like planets and solid cores of giant planets account for more than $\sim 10^{-3}$ of the stellar mass. Therefore, in the parameter space where equation (25) requires more small grains than $\sim 10^{-3}$ of the stellar mass, the model does not appear realistic.

5 DISCUSSION

In this paper we have argued that it is quite likely that planets may form around SMBHs in self-gravitating $\lesssim$ parsec-scale discs as a complement to the star formation process that is known to occur there. We have also argued that the geometrical arrangement of different rings of stars and planets may be very misaligned and should thus lead to very energetic collisions between solids from different stellar discs. This is certain to fuel fragmentation cascades similar to those occurring around stars (Wyatt 2008) except for the much more extreme collision velocities. We have found (Section 3) that smaller solid bodies, e.g. smaller than $\sim$ hundreds of km in diameter, are rapidly destroyed in catastrophic collisions. Solid objects larger than $\sim$1000 km in diameter should feed fragmentation cascades for astrophysically interesting time-scales, e.g. millions of years (equation 8). We have then proceeded to consider whether small grains, presumably the end product of the fragmentation cascade, can explain the observed AGN obscuration (Section 4). We shall now collect the physical constraints we obtained there in order to make observational predictions and thus test the model further.

5.1 No obscuring torus near Sgr A*

The best observed SMBH is Sgr A* in the centre of our Galaxy, as discussed in the Introduction. The column density of absorbing material in the line of sight to Sgr A* is $N_{\rm H} \lesssim 10^{23}$ cm^{-2} (Baganoff et al. 2003), and it appears that most of that is outside the central parsec of the Milky Way (e.g. Muno et al. 2004). Far-infrared observations show that the absorbing column density of the central $\sim$2 pc region near Sgr A* is $N_{\rm H} \lesssim 10^{22}$ cm^{-2} (Zylka et al. 1995; Etxaluze et al. 2011).

At the same time we know that there was a star formation event $\sim$6 Myr ago, with total stellar mass less than $M_{\rm t} \sim 10^4\,{\rm M}_{\odot}$ (Paumard et al. 2006), and that the geometrical arrangement of the stars is far from flat (Bartko et al. 2009). If these massive (Bartko et al. 2010) stars also came with asteroids and comets then a fragmentation cascade is expected.

However, we argue that the Sgr A* star formation event simply did not make enough stars to create a significant fragmentation cascade. First, assuming generously that the total mass of 'new' solid material is $M_Z = 10^{-4} M_{\rm t} \lesssim 1\,{\rm M}_{\odot}$, we estimate (cf. Section 4.2.2) the maximum absorbing column density of these solids if spread around as fine grains: $N_{\rm H} \sim M_z/(2\pi R^2 m_{\rm H} \zeta_{\rm met}) \approx 10^{22}$ cm^{-2} for $R = 0.3$ pc. This is comparable to the deduced $N_{\rm H}$ in the central parsec (Etxaluze et al. 2011). Furthermore, the collisional time-scale for the cascade to develop for Sgr A* stars is $\sim 2 \times 10^9$ yr (cf. equation 8 for the parameters used above and $D_8 = 1$). Physically, such a tenuous cascade is unable to engage the largest bodies in which most of the solid mass is stored (at least in the Solar system). Furthermore, the mass spectrum of the young 'disc' of stars in the central parsec of the Milky Way is unusually top heavy, with at least an order of magnitude deficit of solar-type stars (Nayakshin & Sunyaev 2005; Bartko et al. 2010), and therefore it is not clear whether asteroids and comets managed to form in the usual numbers around these massive stars.

We thus conclude that it is very unlikely that a rather limited star formation event which occured in the central parsec of the Milky

Way, $M_t \lesssim 10^4\,M_\odot$, could have produced enough solids to make a detectable obscuring torus.

5.2 No obscuring cascades at low accretion rate AGN

The example of Sgr A* considered above demonstrates that isolated and limited star formation episodes inside the central parsec of AGN may be insufficient (even under most generous assumptions) to provide a significant enough amount of solids to initiate significant fragmentation cascades. We shall estimate the minimum total mass in the circumnuclear AGN star formation event(s) that could provide enough solids for a given obscuring column density N_H.

The tori for low-luminosity objects are expected to be physically small, e.g. $R \lesssim 0.1$ pc (the torus size seems to be consistent with the location where grains would sublimate, e.g. see fig. 4 in Kishimoto et al. 2011). The total mass of small grains needed to account for a given N_H is given by equation (13) as $M_a \sim 3\,M_\odot (R/0.1\ \mathrm{pc})^2 N_{23}$. The minimum mass in comets and asteroids, M_Z, should be at least this large, obviously, so $M_Z \gg M_a$. If $M_Z = \delta_Z M_t = 10^{-4}\delta_{-4} M_t$, then

$$M_t \gg 3 \times 10^4\,M_\odot (R/0.1\ \mathrm{pc})^2 N_{23}/\delta_{-4}\ . \quad (26)$$

We conclude that, realistically, a star formation event with at least 10^5–$10^6\,M_\odot$ of stars is required to make an obscuring torus. It is theoretically uncertain how much gas is accreted on to the SMBH during such star formation events in the inner parsec (see Nayakshin, Cuadra & Springel 2007; Zubovas, King & Nayakshin 2011). However, if we assume that the AGN activity phase lasted for $\sim 10^7$ yr, and that only a small fraction of the gas was accreted on to the SMBH, then the average accretion rate is $\dot{M} \ll 0.01$–$0.1\,M_\odot\,\mathrm{yr}^{-1}$.

Further, at a low enough accretion rate in the AGN disc the star formation turns off completely because the disc is no longer self-gravitating (e.g. Paczyński 1978; Collin & Zahn 1999). Consider the case $M_8 = 1$ as an example. Fig. 1 in Goodman (2003) shows that independently of the viscosity prescription in the disc, the innermost 0.01–0.1 pc are gravitationally stable for accretion rates lower than about $10^{-4}\,M_\odot\,\mathrm{yr}^{-1}$. Therefore, no star or comet/asteroid formation is expected at such low accretion rates.

If the scaling between an average accretion rate in the disc on sub-pc scales and the AGN accretion rate were clear, this could be mapped into a luminosity-dependent prediction for AGN obscuration. However, one should of course keep in mind the caveat that AGN luminosity could vary significantly with time on time-scales shorter than those required for a significant evolution of the collisional cascades. Thus, there could be sources that are presently in the LLAGN state but were much more active in the recent past, and still have enough solid debris needed for the AGN obscuration cascade.

5.3 No obscuring cascades in quasars

Similarly, we make a broad brush definition of a quasar as an AGN accreting gas at nearly the Eddington accretion rate, setting $l_{bol} \sim 1$. In this case, $l_{-2} = 100 l_{bol} \sim 100$, and equation (25) demands an unreasonably high fractional mass in the small grains:

$$\frac{M_a}{M_*} > 1.5 \times 10^{-2} \frac{\epsilon_* l_{bol}^2 f_{-1}^2}{a_{\mu m} T_3^4}\ . \quad (27)$$

Even for the solar abundance gas, for which $f_{-1} = f_d/0.1 = 0.1$, the requirements are still not very comfortable. Further, M_a is the total mass of the small grains. Since these are fed by the fragmenting cascade of the larger bodies, we would expect the mass in the solid bodies to be much higher than that in the small dust. This would correspondingly increase the required mass of solids in equation (27).

Physically, the inability of our model to provide obscuration for Eddington-limited sources is due to the large radiation pressure of the quasar in such sources. This requires the torus to be very massive (equation 17); in fact too massive for a torus made by a fragmentation cascade.

5.4 Tori in intermediate-luminosity AGN: physically small

We find that intermediate-luminosity AGN, which we operationally define as $l_{bol} \sim 0.01$, appear to be able to both host a starburst to make the solids for the cascade and also make enough stars to provide the internal pressure support. The fraction of solids that should be put into asteroids does not appear excessive in this case either (equation 25).

One interesting aspect of the model, however, is that the resulting obscuring tori must be relatively small. Rescaling equation (23), we have

$$R_{pc} \approx 0.1 T_3^{-2} l_{-2}^{1/2} M_8^{1/2}\ . \quad (28)$$

Such small torus sizes are reasonably consistent with observations. It is interesting to note that if we were to consider a torus much larger than this, say by an order of magnitude, then we would again run into the mass budget problem for solids (cf. equation 24).

Note that optically thin 'tori' of larger physical extent could, however, be made by some fraction of the grains lost to an outflow from the AGN.

5.5 Large dust in AGN tori

The silicate spectral feature near 9.7 μm is surprisingly weak in typical AGN spectra (e.g. Shi et al. 2006; Hao et al. 2007). In addition, there is also a discrepancy in the inferred column density of neutral hydrogen via observations in the optical and via X-rays. A number of authors argued that these peculiarities of AGN absorbers point to 'anomalous' properties of the AGN dust with regard to Galactic dust, and suggested that the AGN dust particles may be larger, e.g. $a \gtrsim 1$–10 μm (e.g. Laor & Draine 1993; Brandt, Fabian & Pounds 1996; Maiolino, Marconi & Oliva 2001a,b). Our model is not detailed enough for us to be able to predict the size distribution of smaller grains and to compare directly with the 'peculiar' AGN dust. However, simply the fact that the dust in our model results from the fragmentation cascade of larger bodies suggests that such dust should be physically larger than its Galactic counterpart. Therefore, large dust in AGN tori, if confirmed with future observations, could originate in the collisional cascade discussed here. Small dust may also be present, if brought in from outside by gas inflow, as argued in Section 4.2.3, or if fragmentation cascade continues to very small, $a \ll$ μm, scales.

6 CONCLUSIONS

We have suggested that solid bodies, from asteroids and comets to large planetary cores, may form in AGN accretion discs due to gravitational instability of the latter. These star and planet formation episodes are likely to occur in randomly oriented planes and thus result in a quasi-spherical distribution of stars and solids. The solids from different discs must then collide at velocities of the order of $1000\ \mathrm{km\,s^{-1}}$, leading to fragmentation cascades that can split even the largest bodies.

We have noted that such cascades are likely to grind the solids all the way into microscopic dust. The small dust particles must absorb and re-radiate the AGN luminosity efficiently. This may be relevant to the well known but still poorly understood AGN obscuration. We have attempted to put various physical constraints on this picture. We have found that such asteroid-fed tori may only work for relatively mildly bright AGN, whereas in AGN approaching their Eddington limits the dust would be driven away by the radiation pressure. Also, the least-luminous AGN, such as Sgr A*, are unlikely to host strong enough starbursts. Solid bodies in this case are not numerous enough to fuel strong fragmentation cascades that could produce an observationally significant amount of microscopic dust.

We should also point out that the fragmentation cascades discussed here may co-exist with 'conventional' gas-rich AGN tori (Krolik & Lepp 1989) made by other means, such as outflows or inflows of gas or supernova explosions. If these are not co-spatial with the cloud of solid bodies considered here, then they are independent of each other. If the conventional torus is co-spatial with the fragmentation cascade then the cascade may be an additional source of dust particles.

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