AGN flickering and chaotic accretion

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ABSTRACT

Observational arguments suggest that the growth phases of the supermassive black holes in active galactic nuclei have a characteristic time-scale $\sim 10^5$ yr. We show that this is the time-scale expected in the chaotic accretion picture of black hole feeding, because of the effect of self-gravity in limiting the mass of any accretion-disc feeding event.

Key words: accretion, accretion discs – black hole physics – galaxies: active – quasars: super-massive black holes – galaxies: Seyfert – X-rays: galaxies.

1 INTRODUCTION

In a recent paper, Schawinski et al. (2015, hereafter SKBS) show that nearby active galactic nuclei (AGN) undergo cycles ('flickering') with a characteristic time-scale. The cycle starts as X-ray emission turns on. Until enough time elapses for X-ray and UV photoionization to produce the optical appearance of an AGN, the system is in the 'optically elusive AGN' or 'X-ray bright optically inactive galaxy' (XBONG) phase. Once photoionization is achieved, the usual AGN phase follows, with both X-ray and optical signatures present. Most of the growth of the supermassive black hole (SMBH) occurs in this phase. This ends as the X-rays turn off, and a light echo phase (as seen in 'Hanny's Voorwerp') may appear after it. SKBS show that the expected duration of photoionization, together with the observed fraction of optically elusive AGN, gives an estimate of the typical lifetime of the AGN phase of a galaxy as

$$t_{\rm AGN} \sim 10^5 \text{ yr.} \tag{1}$$

This number appears to be effectively independent of the galaxy sample used (SKBS). Note that this argument says nothing about the recurrence time-scale of the growth events, only their duration.

In this Letter, we show that the picture of chaotic accretion on to SMBH introduced by Sanders (1981) and developed by King & Pringle (2006) gives a simple explanation for both the characteristic growth time-scale (equation 1) and its similarity for all types of nearby AGN.

2 CHAOTIC ACCRETION

Sanders (1981) first suggested a picture of accretion on to an SMBH which occurs via a sequence of randomly oriented accretion discs. Several authors have since revived this idea (e.g. Moderski, Sikora & Lasota 1998, in discussing the radio properties of quasars). King & Pringle (2006) pointed out that it readily accounts for the lack

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of any correlation between the directions of AGN jets (and so presumably SMBH spin axes) and the geometry of the host galaxy, and secondly that it allows the spin rate of the SMBH, and so its accretion efficiency, to remain low. This second point in turn means that the Eddington limit corresponds to a relatively high mass accretion rate, allowing rapid growth of the SMBH mass to the values $\sim 10^9$-10^{10} $M_\odot$ observed at redshifts $z \sim 6$ (e.g. Barth et al. 2003; Willott, McLure & Jarvis 2003; Wang et al. 2015) even from a stellar initial mass.

King & Pringle (2006) showed that the necessary condition for low SMBH spin is that most accretion-disc episodes have total angular momentum $J_{\rm d} \lesssim J_{\rm h}$, where $J_{\rm h}$ is the hole's spin angular momentum. This condition means that the disc and SMBH spin end up counter-aligned in about half of all the cases. The greater lever-arm of the innermost stable circular orbit (ISCO) in retrograde cases means that the net effect of randomly oriented accretion events is to spin the hole down. In calculating the predicted spin and mass evolution of SMBH, King, Pringle & Hofmann (2008) showed that the requirement $J_{\rm d} \lesssim J_{\rm h}$ is in general easily satisfied, since the total mass of a disc episode is limited by the self-gravity constraint (Pringle 1981; Frank, King & Raine 2002):

$$M_{\rm d} \sim \frac{H}{R} M. \tag{2}$$

Here H/R is the disc aspect ratio, and M the SMBH mass. This constraint means that discs become self-gravitating outside some radius $R_{\rm sg} \sim 0.01$ pc (Collin-Souffrin & Dumont 1990; Shlosman, Begelman & Frank 1990; Huré et al. 1994; King & Pringle 2007). Cooling times in these regions are so short that this is likely to result in star formation rather than accretion (Shlosman & Begelman 1989; Collin & Zahn 1999).

The importance of the self-gravity constraint goes wider. As discussed by King & Pringle (2007), disc self-gravity is a fundamental barrier to accretion: no disc event forming outside $R_{\rm sg}$ – i.e. with initial specific angular momentum $\gtrsim (G M R_{\rm sg})^{1/2}$ – can easily contribute to central accretion. We expect that most of the gas initially at radii $R > R_{\rm sg}$ either forms stars, or is expelled by those stars which

do form on a rapid (almost dynamical) time-scale. Gas initially at radii $R < R_{sg}$ must form a standard accretion disc, gradually draining on to the black hole and powering the AGN. King & Pringle (2007) show that for local, low-luminosity AGN, fuelling by well-separated episodes of this type explains observational features such as the luminosity function for moderate-mass black holes, and the presence and location of a ring of young stars observed about the Galactic Centre.

We conclude that all SMBH feeding must largely come from discs with initial specific angular momentum small enough for them to form at radii $R \lesssim R_{sg}$. As a result, disc events cannot last longer than the time for accretion to drain the mass from within R_{sg}. So the maximum duration of a disc event is

$$t_{sg} \sim \frac{M_d}{\dot{M}} \sim \frac{H M}{R \dot{M}}, \tag{3}$$

where $\dot{M}$ is the average accretion rate.

In AGN discs, the aspect ratio is always small, and almost independent of parameters, i.e.

$$\frac{H}{R} = 1.94 \times 10^{-3} \alpha_{0.03}^{-1/10} \eta_{0.1}^{-1/5} \dot{m}^{1/5} M_8^{-1/10} r^{1/20} \tag{4}$$

(cf. King et al. 2008). Here $\alpha = 0.1\alpha_{0.1}$, $\eta = 0.1\eta_{0.1}$ and $\dot{m} = \dot{M}/\dot{M}_{Edd}$ are the standard viscosity parameter, the accretion efficiency and Eddington accretion ratio, respectively, and $M_8 = M/10^8 \, M_\odot$, $r = R/R_g$, with R_g the gravitational radius GM/c^2.[1] Since H/R is insensitive to any of these parameters we take $H/R \simeq 2 \times 10^{-3}$, and so equation (3) becomes

$$t_{sg} \sim 10^{-3} t_{Sal} \dot{m}^{-1} \sim 10^5 \dot{m}^{-1} \, yr, \tag{5}$$

where $t_{Sal} = M/\dot{M}_{Edd} \simeq 4 \times 10^7 \eta_{0.1}$ yr is the Salpeter time-scale. A full calculation (cf. King & Pringle 2007) gives

$$t_{sg} \sim 1.7 \times 10^5 \alpha_{0.1}^{-2/27} \eta_{0.1}^{22/27} \dot{m}^{-22/27} M_8^{-4/27} \, yr. \tag{6}$$

King & Pringle (2007) show that an AGN luminosity function close to the observed one (Heckman et al. 2004) follows if the initial value of $\dot{m}$ is ~1, fixing the luminosity evolution of each disc event as

$$L \simeq L_{Edd} [1 + (t/t_{var})]^{-19/16}, \tag{7}$$

where L_{Edd} is the Eddington luminosity and t_{var} is t_{sg} with $\dot{m} = 1$, i.e.

$$t_{var} \sim 1.7 \times 10^5 \alpha_{0.1}^{-2/27} \eta_{0.1}^{22/27} M_8^{-4/27} \, yr. \tag{8}$$

So chaotic accretion predicts a mass-growth time-scale t_{var} of AGN variation very close to what SKBS deduce from observations. This result is almost independent of AGN parameters. AGN may of course vary in other ways (e.g. through the thermal–viscous disc instability, cf. Burderi, King & Szuszkiewicz 1998) but only if these have shorter time-scales than the mass-supply time t_{var}. Such mechanisms cannot have a major effect on SMBH mass growth, since the self-gravity constraint implies that much of this is at near-Eddington rates (cf. equation 7 above).

3 DISCUSSION

The simplicity of the derivation of the time-scale t_{var} is striking. It depends only on the fact that the disc aspect ratio H/R is always ~10^{-3} for AGN accretion discs, and so is an immediate and inescapable consequence of chaotic accretion. The very tight limit $R_{sg} \lesssim 10^{-2}$ pc on the formation radius of AGN discs, as derived by King & Pringle (2007), is independently supported by the variation time-scale that SKBS deduce from observation. It implies that gas accreting on to SMBH must have been 'aimed' very precisely towards them, and is significantly tighter than the limit $R_{circ} \lesssim 1$ pc needed for the viscous time-scale to be less than the Hubble time. A potential explanation for these stringent limits may be that SMBH feedback itself tends to provoke very radially directed accretion (Dehnen & King 2013). Whatever the mechanism driving accretion, the emerging picture of SMBH feeding appears to suggest that it is likely to be chaotic on small scales of length, time and mass, rather than orderly.

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[1] Larger values of H/R can be produced if the disc is assumed to be bathed in AGN emission reradiated by a very close-in warm absorber of similar size $\lesssim 10^4$ Schwarzschild radii, cf. Loska, Czerny & Szczerba (2004). However recent observations by Tombesi et al. (2013) suggest that the likely distance of such components is a factor ~10^4 greater, making the reradiation effect negligible.

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