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Close stars and accretion in low-luminosity active galactic nuclei

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ABSTRACT

Quasar accretion discs are believed to form stars by self-gravity. Low-luminosity active galactic nuclei (LLAGNs) are much dimmer galactic centres, and are often believed to be quasars that ran out of gaseous fuel. LLAGN accretion discs should thus coexist with thousands to millions of stars or protostars left from the previous stronger accretion activity. In principle, these stars may produce several important effects: (i) contribute to the optical/ultraviolet spectra of some LLAGNs; (ii) the dusty discs could reprocess stellar radiation in the infrared frequencies and then dominate the LLAGN spectra in that region; (iii) deplete the (accretion) gas disc much faster than it can accrete on to the supermassive black hole; (iv) stars, individually or in groups, may slow down and modulate the accretion flow significantly due to their inertia. In this way they may produce the LLAGN cut-off discs; (v) alternatively, frequent enough stellar collisions and resulting stellar disruptions could keep the inner disc empty. Here we explore these ideas. We find that, despite 'low' luminosities of LLAGNs, unrealistically high stellar densities are required to make a sizable radiative contribution to the *Hubble Space Telescope* optical/ultraviolet spectra of these galactic nuclei. Stellar contribution to the infrared spectrum is more likely. Further, if LLAGNs are in a quasi-steady state for as long as 10^7 yr or more, too high stellar densities would again be required to significantly affect the dynamics of accretion flow. However, if LLAGNs are 'short-lived' phenomena, e.g. $t \lesssim 10^5$ yr, the low-activity states of quiescence–outburst cycles, then embedded stars may be much more important through the mass effects (iii)–(v). With observations of LLAGNs becoming progressively better, it will be more and more difficult to neglect the presence of close stars in and around nuclear accretion discs.

Key words: accretion, accretion discs – stars: formation – quasars: general.

1 INTRODUCTION

Low-luminosity active galactic nuclei (LLAGNs) are galactic centres intermediate in luminosity and in some key properties between quasars (bolometric luminosity $L_\mathrm{b} \sim 10^{46}$ erg s^{-1}) and inactive galactic centres (IGCs), such as our own (Sgr A*), whose luminosity is about $L_\mathrm{b} \sim 10^{36}$ erg s^{-1}. LLAGNs are also known as low ionization nuclear emission-line regions (LINERs; Heckman 1980) or as 'dwarf' Seyfert nuclei (e.g. Ho, Filippenko & Sargent 1997, 2003). Typical nuclear bolometric luminosities of these sources are $L_\mathrm{b} \lesssim 10^{42}$ erg s^{-1} (e.g. Ho 2003). It is well known that most present-day galaxies harbour supermassive black holes (SMBHs), implying that LLAGNs and IGCs too had to be bright accreting sources at some earlier times. LLAGNs and IGCs are thus quasar relics or quiescent phases of a long-term evolution of galactic nuclei. Some of the processes operating in the quasar phase may have long-lasting effects and continue to influence SMBH activity in the present dim epoch. One such process is star formation inside quasar accretion discs due to self-gravity at distances greater than $\sim 10^3$ Schwarzschild radii (e.g. Paczyński 1978; Kolykhalov & Sunyaev 1980; Shlosman & Begelman 1989; Collin & Zahn 1999; Goodman 2003), where $R_\mathrm{S} = 2GM_\mathrm{BH}/c^2$, the Schwarzschild radius for the black hole with mass M_BH. The goal of this paper is to investigate some of the possible effects of the presence of these close and fast moving stars on the LLAGN phenomenon.

Let us summarize the observational and theoretical framework in which bright AGNs, LLAGNs and inactive galactic centres are currently understood. Quasar accretion discs are believed to be the 'standard' accretion discs (Shakura & Sunyaev 1973), possibly supplemented by an X-ray emitting corona. The cold accretion disc apparently extends down to the last stable orbit, as evidenced by a very prominent thermal-like ultraviolet (UV) feature called the big blue bump (BBB) and by the broad Fe Kα lines observed in many cases (it is our personal opinion that the non-detection of broad Fe Kα lines in other sources is caused by an overionization of the accretion disc surface). The near-Eddington luminosities of quasars, short time-scale variability, and the high radiative efficiency with which most

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of the SMBHs are inferred to have grown (Yu & Tremaine 2002) are also best explained in the context of the standard accretion discs because they indeed have very high radiative efficiency.

LLAGNs, and our Galactic Centre (GC) black hole, Sgr A*, are distinctly different in this regard, possibly requiring a radiatively inefficient accretion. *Chandra* X-ray observations constrain the amount of hot gas at the capture radius in Sgr A* and M87 (Baganoff et al. 2003; Di Matteo et al. 2003), which allows one to estimate the Bondi accretion rate on to the SMBHs. For other sources where direct X-ray data are not constraining enough, Ho (2003) notes that the centres of the galaxies hosting LLAGNs should be filled with hot winds from young stars (similar to our GC), yielding an accretion rate estimate. In addition, the accretion rate through a cold accretion disc may be estimated by using the optical/UV data in some LLAGNs (e.g. Quataert et al. 1999; Ptak et al. 2004). All of these methods lead to the same conclusion – the expected luminosity from a thin standard accretion disc fed at the deduced accretion rate is some one to four orders of magnitude higher than actually observed.

In addition, in stark contrast to quasars and Seyfert galaxies, LLAGNs do not show the BBB in their spectra (Ho 1999), have no short time-scale X-ray variability and no broad Fe Kα lines (e.g. Dewangan et al. 2004; Ptak et al. 2004). This strongly argues for the absence of the cold accretion discs in the inner $\sim 10^2$–$10^3 R_{\rm S}$. Theoretical interpretation of this fact is that the cold disc 'evaporates' at a few hundred to a few thousand $R_{\rm S}$ (e.g. Quataert et al. 1999; fig. 2 in Ho 2003; Ptak et al. 2004) to form an inner hot non-radiative accretion flow (e.g. Narayan & Yi 1994; Blandford & Begelman 1999). The most frequently discussed evaporation mechanism is that of Meyer & Meyer-Hofmeister (1994). If the ions of the hot flow are much hotter than the electrons, then the flow is radiatively inefficient and is much less luminous than the standard flow, explaining the discrepancy. In the least luminous (in terms of $L_{\rm b}/L_{\rm Edd}$, where $L_{\rm Edd} = 1.3 \times 10^{46} M_8$ erg s^{-1}, the Eddington limit for the black hole mass $M_8 = M_{\rm BH}/10^8$ M$_\odot$) cases, such as Sgr A*, it is possible that a cold accretion disc does not even exist (e.g. Falcke & Melia 1997; Narayan 2002).

The best studied example of an inactive galactic centre is the centre of our own galaxy, Sgr A*. Genzel et al. (2003) – see also Levin & Beloborodov (2003) – discovered that most of hot massive and luminous 'He stars' in the GC lie in one of the two stellar discs.[1] The radial sizes of the discs are a fraction of a parsec. A major puzzle is the youth of the He stars, e.g. $t < 10^7$ yr, because the current gas densities near Sgr A* appear too low to initiate star formation. McMillan & Portegies Zwart (2003) have explored the idea that the stars originate in a star cluster some tens of parsec away of the SMBH. The star cluster is brought in by the dynamical friction with the field stars and is eventually dissolved by the tidal influence of the SMBH. However, they found that only very massive $M \gtrsim 10^5$ M$_\odot$ star clusters could sink rapidly enough.

In our view, it is most likely that the young He stars were formed by the self-gravity in two massive accretion discs existing in earlier times (Genzel et al. 2003; Levin & Beloborodov 2003; Nayakshin, Cuadra & Sunyaev 2004). In the case of the GC, these young stars actually dominate and determine the SMBH activity, because their radiative output is some $\sim$ five orders of magnitude greater than that of the accretion flow, and because the hot winds produced by these stars are believed to be the main source of fuel for Sgr A* (e.g. Coker & Melia 1997).

Given the theoretical expectations for quasars (e.g. Syer, Clarke & Rees 1991) and the observational evidence for Sgr A*, it appears likely that important interactions between close stars and the accretion flow may be taking place in LLAGNs as objects intermediate between quasars and Sgr A*. Star formation may continue in the LLAGN phase (e.g. see fig. 1 in Goodman 2003; also Milosavljevic & Loeb 2004). Quite generally, close stars should assume more prominent roles in the LLAGN (and IGC) phase than they do in quasars because the mass and the luminosity output of the gaseous accretion disc are modest in these sources. The possible effects of the close stars can be divided into two categories: the luminosity and the mass effects. The former are due to the combined stellar luminosities, whereas the latter are due to stellar mass – dynamical and accretion effects. We find that the luminosity effects, besides reprocessing of the stellar light into the infrared region, are unlikely to be important due to existing observational constraints. The mass effects are much more plausible especially if the disc inner regions are 'light' as is the case when the disc is unstable to a limit cycle instability (e.g. Lin & Shields 1986; Siemiginowska, Czerny & Kostyunin 1996) or is emptied out in the inner part for other reasons.

2 SELF-GRAVITY IN QUASAR DISCS

We shall not discuss the implications of self-gravity for quasar discs because these have been investigated previously by a number of workers (e.g. Paczyński 1978; Kolykhalov & Sunyaev 1980; Shlosman & Begelman 1989; Goodman 2003). Quasars are believed to be accreting near the Eddington limit and hence their accretion discs need to be quite massive. The discs are expected to form stars at radii for which the Toomre (1964) parameter satisfies

$$Q = \frac{c_{\rm s}\Omega}{\pi G \Sigma} \simeq \frac{\Omega^2 H}{\pi G \Sigma} = \frac{H M_{\rm BH}}{\pi \Sigma R^3} \approx \frac{M_{\rm BH}}{M_{\rm d}(R)} \frac{H}{R} < 1 \tag{1}$$

where $c_{\rm s}$ is the isothermal sound speed of the disc, Ω is the Keplerian circular rotation frequency, $\Sigma(R)$ is the disc column depth at radius R, H is the disc half-thickness (pressure height-scale), and finally, $M_{\rm d}(R) = \Sigma \pi R^2$ is approximately the disc mass within radius R. Following Goodman (2003), the radii which satisfy this conditions in the standard accretion disc are

$$R > R_{Q=1} \simeq 2.7 \times 10^3 R_{\rm S} \left(\frac{\alpha_{-1} \dot{m}^2}{M_8} \right)^{2/9}, \tag{2}$$

where α_{-1} is the normalized Shakura–Sunyaev viscosity parameter, $\dot{m} = \dot{M}/\dot{M}_{\rm Edd}$, where $\dot{M}_{\rm Edd} = L_{\rm Edd}/\epsilon c^2$, with radiative efficiency $\epsilon = 0.1$. In this paper we shall use the notations in which $\alpha_{-1} \equiv \alpha/10^{-1}$, $\dot{m}_{-3} \equiv \dot{m}/10^{-3}$, etc.

It has been argued that, in addition to $Q \lesssim 1$, a second condition for star formation by self-gravity in accretion discs must be fulfilled: the cooling time should be shorter than a fraction of the Keplerian rotation period (e.g. Shlosman & Begelman 1989; Gammie 2001). Recent simulations by Johnson & Gammie (2003) demonstrated that the instability domain can be larger. In the non-linear instability stage, the local cooling time may be orders of magnitude smaller from that found in the unperturbed disc model. Therefore, it appears

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[1] Note that there are also less massive and less luminous stars closer in to Sgr A* (e.g. Genzel et al. 2003; Ghez et al. 2004) whose angular momentum vectors are distributed in a more isotropic way. The constraint on the age of those stars is on average less stringent. Further, two-body gravitational relaxation (e.g. Alexander & Livio 2004) and interaction with the SMBH (Levin & Beloborodov 2003) is far more rapid for these innermost stars, naturally accounting for their near isotropy.

difficult to prevent even the marginally stable, $Q \sim 1$, optically thick disc from fragmenting and forming stars.[2]

Because the formation of gravitationally bound structures is extremely fast (Toomre 1964), it is then feared that most of the disc mass would be used up to build up stars rather than feed the SMBH. In fact, recent numerical simulations of Rice et al. (2003) showed exactly this outcome in the context of a protoplanetary disc (of course, there the formation of planets is a welcome outcome). Sirko & Goodman (2003) demonstrated that the amount of heat required to stop star formation in the disc outer regions is excessive (i.e. larger than L_{Edd} for a typical quasar), and moreover the observed quasar spectral energy distributions (SEDs) rule out such a heating. Thus, it seems inevitable that stars will form in quasar discs at radii $\gtrsim 10^3 R_{\mathrm{S}}$. Having formed there, the stars can migrate (inspiral) radially through exchange of the angular momentum with the disc (e.g. Syer et al. 1991), so their radial distribution may evolve significantly on time-scales that are long enough.

It is not clear how much mass would be converted to stars in a single accretion outburst episode, but if we assume that this is a fraction $q < 1$ of the disc mass, then obviously

$$M_* N_* = q M_{\mathrm{d}} \approx \frac{q}{Q}\frac{H}{R} M_{\mathrm{BH}} \simeq 3 \times 10^5\,\mathrm{M}_{\odot}\,\frac{q}{Q} M_8, \tag{3}$$

where we set $H/R \sim 3 \times 10^{-3}$ (see equation 5), and N_* and M_* are the total number of stars created and a typical stellar mass, respectively. It is also unclear how exactly this stellar distribution evolves with time under the interaction with the accretion flow, because stars may be swallowed or tidally disrupted by the SMBH if they migrate close enough (Syer et al. 1991), they may explode as supernovae (Syer et al. 1991; Rozyczka, Bodenheimer & Lin 1995), destroyed by direct star–star collisions, and evolve under the influence of long-range two-body interactions (e.g. Bahcall & Wolf 1976).

It is outside the scope of this paper to discuss ways for quasars to maintain high enough mass transfer rates into the SMBHs when the self-gravity sets in their accretion discs. Now, suppose that the quasar mass supply has substantially decreased, so that most of the gaseous disc mass has been used up, and that some number of the 'original' self-gravity created stars is still caught up in the disc. The quasar presumably becomes a LLAGN. What would then be the role of such stars?

3 DIRECT CONTRIBUTION TO LLAGN SPECTRUM

Even with the *Hubble Space Telescope* (*HST*), except for very few nearby galaxies, galactic centres are not resolvable to scales better than ~1 pc in the optical/UV. Stars formed in a self-gravitating disc at a distance of $R = 0.04\,(M_{\mathrm{BH}}/4 \times 10^6\,\mathrm{M}_{\odot})\,r_5$ pc, where $r = R/R_{\mathrm{S}}$ and $r_5 = r/10^5$, cannot be directly separated out from the accretion disc spectrum. In addition, the galactic centres are viewed through a large column depth of galactic stars (i.e. the galactic bulges). However, Filippenko & Sargent (1985) and Ho et al. (1997), created a large template of galaxies without or with very weak emission lines. Using a sophisticated technique to fit the absorption lines in the spectra of LLAGNs, they were able to subtract out contribution of galactic stars, and to obtain the nuclear (very weak compared to the galaxy) continuum and broad emission lines of LLAGNs.

The stars that we are interested in are very close to the SMBH, and their circular Kepler velocities are $\upsilon_{\mathrm{K}}(r) \approx 2000\, r_4^{-1/2} \approx 2000(0.1\,\mathrm{pc}\, M_8/R)^{1/2}$ km s^{-1}, where $r_4 = r/10^4$. Because the galaxy template contains spectra with FWHM velocities of $\lesssim$500 km s^{-1} (Ho et al. 1997), it is most likely that the Doppler-broadened spectra of the inner stars in the LLAGNs would be counted as the continuum emission (Ho, private communication). Can such stars make a non-negligible contribution to the LLAGN nuclear spectrum? Two cases exist.

3.1 Hot massive young stars

The stellar spectrum of the inner central parsec of our GC is dominated by hot young stars. It is thus interesting to compare its spectrum with the better of the available nuclear LLAGN spectra. M81 is a nearby LLAGN, with the SMBH mass estimated at a value very close to that of Sgr A* (e.g. Ghez et al. 2003; Schödel et al. 2003), $M_{\mathrm{BH}} = 4 \times 10^6\,\mathrm{M}_{\odot}$. The M81 nuclear infrared to UV spectrum is shown as thick data points and upper limits in Fig. 1 as compiled in table 2 of Ho (1999). Ho (1999) argues against a significant intrinsic dust extinction in LLAGNs. The spectrum of stars in the inner 1 pc in our GC is relatively well known (Mezger, Duschl & Zylka 1996): there is a contribution of ubiquitous low-mass stars with effective temperature $T_{\mathrm{eff}} = 4 \times 10^3$ K, with a combined luminosity of $10^6\,\mathrm{L}_{\odot}$, and there are ~30 hot young stars with the total luminosity of $3 \times 10^7\,\mathrm{L}_{\odot}$ and the effective temperature of $T_{\mathrm{eff}} = 3.5 \times 10^4$ K. This spectrum is shown as a solid curve in Fig. 1 and assumes no extinction (of course we actually observe the GC through some ~30 mag of extinction in the visual).

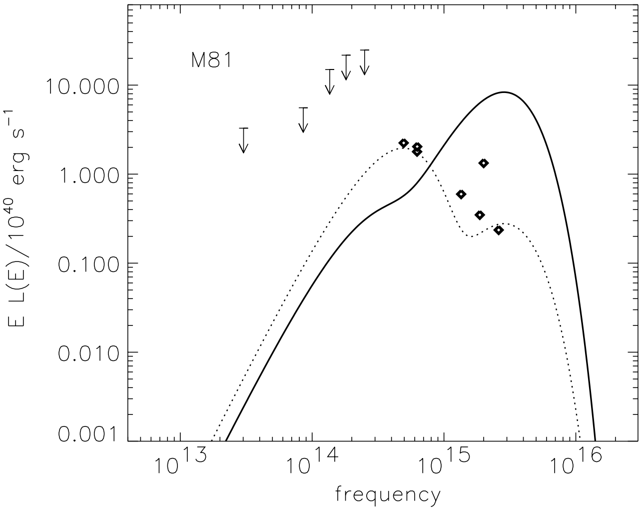

Figure 1. M81 infrared to UV SED compared to the spectrum of the central parsec of the Milky Way (solid curve). The dotted line shows the spectrum of a nuclear star cluster that 'fits' the M81 data. Note that the latter model requires too high a spatial density of stars and hence it is ruled out on physical grounds (see text).

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[2] The anonymous referee made the following remark, with which we partially agree. 'The largest differences between the results of Johnson & Gammie (2003) and that of Shlosman & Begelman (1989) and Gammie (2001) occur in rather limited circumstances – specifically, when the disc temperature is around that of hydrogen ionization so that the opacity is a very strong function of temperature. The most likely region for gravitational instability (i.e. $Q \sim 1$), on the other hand, is probably further out where the temperature is lower (and magnetorotational instabilities are harder to sustain). At these larger radii, there could still be a significant cooling time restriction on when fragmentation can occur.' However, as noted by Johnson & Gammie (2003), most additional physical processes, not included in their simulations, appear to increase the tendency to fragmentation.

Clearly, had there been a similar amount of such hot luminous young stars in M81 as in the GC, these stars would easily outshine the LLAGNs in M81 in the UV band. However, in the GC the vast majority of the hot young stars move with velocities of the order of $\lesssim$500 km s^{-1}, so that the subtraction technique of Ho et al. (1997) would have probably removed them from the nuclear spectrum. In any event, stars moving with such 'low' velocities are outside the radius where most of the accretion flow physics is played out ($\lesssim 10^5 R_{\rm S}$). The results of Ho (1999) thus clearly show that there are no or very few hot young luminous O stars in the inner accretion flow region in most of the LLAGNs (LINERs) as otherwise they would produce a component similar to the BBB.

Because the history of star formation and evolution in an accretion disc are extremely model- and parameter-dependent, it is possible that such young massive stars never formed in the LLAGN accretion disc. It is also possible that these stars have already gone through the supernova phase (e.g. Syer et al. 1991), or are on the red giant branch, thus shifting their spectrum from the UV into the optical frequencies (but see the next section).

3.2 Low-mass stars or evolved red giant stars

The dotted line in Fig. 1 is a very simple model that 'fits' the M81 data much better. In this model the 'low'-mass stars have an average temperature of 6×10^3 K, their total luminosity is 6×10^6 L$_\odot$, and there is just one hot luminous star with $L = 10^6$ L$_\odot$ and $T_{\rm eff} = 3.5 \times 10^4$ K. Clearly, a more realistic model with a power-law mass function could be designed that would easily fit the infrared to UV SED of M81 with no contribution from the accretion on to the SMBH whatsoever.

However, there are several arguments against such a possibility. To appear as an AGN continuum, the spectrum of such stars would have to be strongly smeared, say with random velocities of the order of 2000 km s^{-1} or more. For M81, the mass of the stars would exceed the deduced SMBH mass, thus leading to a direct contradiction with observations. Further, the stellar densities in the inner part of the stellar cluster would be as large as 10^{14} M$_\odot$ pc^{-3} if the stars are main-sequence stars with $M \sim$ M$_\odot$. Such high stellar densities are extremely unlikely because stellar physical collisions and disintegrations would be expected (e.g. Murthy, Cohn & Durisen 1991). If the stars are much more luminous supergiants, then the required stellar number density is much lower, but because of their large radii we find that the collision time is of the same order, i.e. too short. The red giant stars are also easy targets for ablation of mass due to star–disc collisions (Armitage, Zurek & Davies 1996). Finally, there is a deficit of such stars in the inner cusp of our GC (Genzel et al. 2003).

3.3 Infrared spectrum: reprocessing in the disc?

The stellar cusp/cluster could also contribute to heating the gaseous disc, especially its surface layers. If the stars are uniformly distributed within radius R, then the effective temperature of the stellar radiation is $63\, L_{41}^{1/4} (R/{\rm pc})^{-1/2}$ K, where L_{41} is the total stellar luminosity in units of 10^{41} erg s^{-1}. We argued that it is not plausible for the stars to dominate the nuclear optical/UV continuum of LLAGNs, hence it seems unlikely that they would significantly add to the reprocessed disc emission.

This may not be the case, however, because the accretion disc is very thin (equation 5), and only a very small fraction of the luminosity generated by accretion on to the SMBH may impact the outer disc. In contrast, the accretion disc is geometrically thick compared to stars and would reprocess a large fraction of stellar light even if stars are exactly in the disc mid-plane. If stars are on more general orbits (see Section 5), then roughly half of their radiation is reprocessed in the disc, possibly making it important in the mid-infrared region where a 'bare' disc (without surrounding stars) is predicted to be dim. In this case, the distribution of the radiation impinging on the disc will be quite patchy. Therefore, there may be a broad range of temperatures resulting from the stellar illumination of the disc which would obviously lead to a broad infrared feature in the SED of the LLAGN. This feature will be spectroscopically much broader than that resulting from the disc illumination by the single central source (the accreting SMBH), and it may be also variable on time-scales of weeks to years because of bright stars approaching and passing through the disc (e.g. Cuadra, Nayakshin & Sunyaev 2003; Nayakshin & Sunyaev 2003). Stars also heat the disc via bodily impacts (e.g. Norman & Silk 1983; Zentsova 1983) and can increase the effective disc viscosity (Ostriker 1983).

4 EMBEDDED STARS AND DISC ACCRETION

Stars orbiting the SMBH in the inner parsec of the accretion flow will also modify the accretion flow of gas. We assume that the combined mass of stars in this region is much smaller than $M_{\rm BH}$, and we consider the case when the stellar and disc planes coincide exactly. In this limit the relative velocity of a star and the gas in the disc surrounding the star is negligible. Thus, star–disc interactions are qualitatively different. The interaction is best understood based on the analogy between this case and that of a better studied circumstellar disc with embedded (proto)planets. If the star does not open up a radial gap in the disc (see below), then it grows via Bondi-like gas accretion. If the gap is opened, the accretion on to the star slows down significantly. The star, however, continues to interact with the disc due to gravity (essentially via dynamical friction). In both gap/no-gap cases the star can migrate, that is spiral-in, radially. Clearly the flows of gas and stars are not independent.

One note appropriate here is the role of the stellar migration in the disc. An analogy with protoplanetary disc calculations (e.g. Ward 1997; Bate et al. 2003) suggests that this migration could be very fast. The stars could be dragged into the SMBH by the dynamical friction with the gaseous disc on time-scales shorter than the accretion disc viscous time-scales. This process has already been discussed by Syer et al. (1991). However, we point out that the rate of the radial migration strongly depends on the equation of state chosen for the accretion disc. Syer et al. (1991) considered very luminous quasars accreting near the Eddington limit, and suggested that the disc viscosity in the inner radiation–pressure dominated regions (approximately the inner thousand $R_{\rm S}$) is proportional to the gas pressure only. Under this assumption the disc is orders of magnitude more dense than it would have been if the viscosity were proportional to the total pressure (e.g. see the appendix in Stella & Rosner 1984 for the 'non-standard' gas-only contribution to viscosity equations). We find that in the latter case the radial migration of stars becomes very slow in the radiation-supported part of the disc, effectively stalling them there (Cuadra et al., in preparation). In this way the stars may easily survive the quasar epoch until the LLAGN phase, when the accretion rate through the disc decreases and the gas becomes gas pressure dominated at all radii. The subsequent radial migration of the embedded stars is discussed further in Section 4.4.

4.1 Gap formation conditions

A star corotating with the disc interacts with the gas in the disc via gravitational torques (e.g. Goldreich & Tremaine 1980; Lin &

Papaloizou 1986a,b). The linear velocity of gas at radii greater than the radius at which the star circles the SMBH, R, is increased as a result of the interaction with the star. Thus, its angular momentum increases and it moves outward from the star's location. The opposite happens to the gas interior to the star's location. Hence the star pushes the gas away from its radial position. If this effect is strong enough, a radial gap is opened in the disc.

The Hill radius $R_{\rm H}$

$$R_{\rm H} = \left(\frac{M_*}{3M_{\rm BH}}\right)^{1/3} R \tag{4}$$

defines the star's sphere of influence in the disc; dynamics of gas within the sphere is dominated by the star rather than the SMBH.

There are two conditions for formation of the radial gap in the disc. The first is that $R_{\rm H}$ is greater than the pressure scaleheight of the disc, H. Otherwise the gas would be able to overflow the star at vertical heights $z > R_{\rm H}$. The disc height-scale H for gas-pressure standard accretion disc at $r \equiv R/R_{\rm S} \gg 1$ is

$$H/R = 2.5 \times 10^{-3}\, (\alpha M_8)^{-1/10}\, r^{1/20} \dot{m}^{1/5} \tag{5}$$

(see Svensson & Zdziarski 1994). We assume that the accretion disc is not strongly self-gravitating during the LLAGN epoch, i.e. that $Q \gtrsim 1$, because

$$\frac{H}{R_{\rm H}} = 0.26\, (\alpha M_8)^{-1/10}\, r^{1/20} \dot{m}_{-4}^{1/5} \left(\frac{M_8}{m_*}\right)^{1/3} < 1, \tag{6}$$

where $m_* \equiv M_*/{\rm M}_\odot$. The first condition for a gap formation is usually satisfied in LLAGN discs.

The second criterion is that the rate with which the gas is pushed away from the star's location due to gravitational interaction is higher than the rate with which the gap could be filled in due to viscous gas transport. This is possible only when the disc viscosity is low enough. Parametrized in terms of the Shakura–Sunyaev α-parameter, this condition becomes

$$\alpha < \alpha_{\rm min} = \frac{1}{40} \left(\frac{M_*}{M_{\rm BH}}\right)^2 \left(\frac{R}{H}\right)^5 \tag{7}$$

(e.g. Syer et al. 1991). Using the expression for H/R, we obtain

$$\alpha_{\rm min} = 3.8 \times 10^{-5} \frac{m_*^4}{M_8^3}\, r_2^{-1/2} \dot{m}_{-3}^{-2}. \tag{8}$$

It is unlikely that α is as low as this, and hence the low-mass stars are unable to open a gap in the disc of a 'large' SMBH, i.e. $M_8 \gtrsim 1$. However, for $M_{\rm BH} = 4 \times 10^6\ {\rm M}_\odot$, the coefficient in equation (8) is $\alpha_{\rm min} = 0.6$: low-mass stars may open a gap in accretion discs of lighter galactic nuclei. Finally, for $M_8 = 1$ and $m_* = 10$, i.e. a high-mass star with $M_* = 10\ {\rm M}_\odot$, we have $\alpha_{\rm min} = 0.38$, thus a gap formation is again likely.

4.2 No gap: accretion on to embedded stars. Forming an inner hole?

Consider now the cases when the stars are unable to open up a gap. As shown above, a gap is unlikely to form for high-mass black holes, i.e. $M_8 \gtrsim 1$, or when the stars are low-mass stars. Also, gap formation is more problematic at large radii $r_2 \gg 1$. The stars then grow by accretion of gas from the disc (Syer et al. 1991).

4.2.1 Low-mass stars

For low-mass stars, stellar radiation and winds are relatively weak. The accretion of gas on to a low-mass star is then similar to the growth of terrestrial planets in a planetesimal disc (Lissauer 1987; Bate et al. 2003; Tan & Goodman 2004). Because $R_{\rm H} > H$, accretion on to the star is quasi-two-dimensional. The accretion rate is determined by the rate at which differential rotation brings the matter into the Hill sphere,

$$\dot{M}_* = \dot{M}_{\rm H} \sim 4\pi R_{\rm H} H \rho v_{\rm H} \sim 4\pi R_{\rm H}^2 \rho c_{\rm s}, \tag{9}$$

where $\rho = \Sigma/2H$ is the mean disc density. We used the fact that the characteristic gas velocity (relative to the star) at the Hill distance from the star, $v_{\rm H}$, is $v_{\rm H} = R_{\rm H} |\,{\rm d}\Omega/{\rm d} \ln R| \sim c_{\rm s}(R_{\rm H}/H)$ because the angular velocity for Keplerian rotation is $\Omega = c_{\rm s}/H$. Equation (9) is valid as long as $R_{\rm H} > H$ because in the opposite case the gas thermal velocity becomes important and the accretion would proceed at the Bondi rate (e.g. Syer et al. 1991). Of course, $\dot{M}_*$ cannot exceed the Eddington limit value, e.g.

$$\dot{M}_{*,{\rm Edd}} \sim 10^{-3}\, \frac{m_*}{r_*}\, {\rm M}_\odot\ {\rm yr}^{-1}, \tag{10}$$

where $r_* \equiv R_*/{\rm R}_\odot$, the star's radius in solar radii units.

4.2.2 High-mass stars in the disc

The enormous radiation field of luminous high-mass stars pre-heats the disc material at distances $\sim R_{\rm H}$ from the star. If the temperature established is much higher than the unperturbed disc temperature, the flow of gas will be strongly affected. Indeed, $T_{\rm eff}(R_{\rm H}) = [L_*/4\pi\sigma R_{\rm H}^2]^{1/4}$,

$$T_{\rm eff}(R_{\rm H}) = 730\ {\rm K}\ \frac{L_5^{1/4} M_8^{-1/3} r_4^{-1/2}}{(M_*/30\,{\rm M}_\odot)^{1/6}} \tag{11}$$

(where $L_5 \equiv L_*/10^5\ {\rm L}_\odot$), can be larger than the disc effective temperature, $T_{\rm eff,d}$:

$$T_{\rm eff,d} = 110\ {\rm K}\ \left(\frac{\dot{m}_{-4}}{M_8 r_4^3}\right)^{1/4}. \tag{12}$$

The accretion disc next to a high-mass star is thus bloated. At distances from the star $\lesssim R_{\rm H}$, the star's gravity takes over and a thin small-scale circumstellar disc develops. Perpendicular to the disc, strong stellar winds sweep up the colder matter. A sort of torus thus forms around the star. There will be a thin ionized (Strömgren) layer on the side of the torus facing the star. At low disc surface densities appropriate to LLAGNs, high-mass stars lose rather than gain mass from the disc; the winds may cool and condense on the disc surface.[3] The accretion rate on to the massive star is strongly reduced due to the disc pre-heating. The disc accretion on the high-mass stars is completely negligible compared with that on the much more numerous low-mass stars that do not suffer from pre-heating and stellar winds.

The observational appearance of the star will be strongly angle-dependent. Viewed pole-on to the disc, the intrinsic stellar emission is clearly visible, as is the line emission resulting from the disc illumination. However, when viewed at large inclination angles, the stellar emission is hidden from the observer similar to the central regions of type 2 AGN. The optical line emission of the inner part of the 'torus' around the star may still be visible.

Note that, for quasar discs, $\dot{m} \sim 1$ and then $T_{\rm eff,d} \gtrsim T_{\rm eff}(R_{\rm H})$ even for the brightest O stars. In addition, for smaller radii, i.e. $R \sim 100 R_{\rm S}$, the disc pre-heating is unimportant even for LLAGNs.

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[3] Note that neither the hot stellar wind nor the gas evaporated from the disc escape to infinity because the escape temperature is $\sim T_{\rm vir} \sim 3 \times 10^8\ {\rm K} r_4^{-1}$.

4.2.3 Eating the disc from within

As shown previously, the embedded stars gain mass from the accretion disc. Here we consider only the low-mass stars that are certain to dominate the disc–star mass exchange due to their large number. From the standard accretion theory, the gas accretion rate on to the SMBH is

$$\dot{M}_{\rm BH} = 4\pi R H \rho |v_{\rm R}| \sim 4\pi H^2 \rho \alpha c_{\rm s} \tag{13}$$

because $|v_{\rm R}| \sim \alpha\,(H/R)\,c_{\rm s}$ (e.g. Frank, King & Raine 1992). Therefore the rate of accretion on the single star compares to the accretion rate on to the black hole as

$$\frac{\dot{M}_{\rm H}}{\dot{M}_{\rm BH}} \simeq \frac{R_{\rm H}^2}{\alpha H^2} \gtrsim 1 \ \ !! \tag{14}$$

Surprisingly, just one star in a LLAGN disc may consume the disc quicker than the SMBH, leaving little for the SMBH growth. Of course the accretion on to the protostar is limited to $\dot{M}_{*,\rm Edd}$, for one. Pre-heating of the gas by the radiation from the star and the circumstellar accretion disc may decrease the accretion rate further. Nevertheless, even if accretion on a single star is very inefficient compared with equation (9), a large number of protostars in the disc can make up for this, and thus the combined mass accretion on these stars could well exceed that on to the SMBH during the LLAGN phase.

Numerical simulations of protoplanetary discs, e.g. Bate et al. (2003), and especially Rice et al (2003) strongly support this view. In particular, the latter authors show that a self-gravitating disc of 0.1 $\mathrm{M}_\odot$ around a 1-$\mathrm{M}_\odot$ star quickly breaks into about a hundred self-gravitating objects (planets and brown dwarfs). Only a tenth of the initial disc mass was accreted by the central star during the calculation. We suspect this fraction would further decrease if the initial conditions for the calculation started with mass deposition at large radii, as appropriate in the AGN context, rather than with a disc extending down to small radii already. We further notice that the relaxation time for two-body interactions is too long in the AGN context to expect a significant fraction of the low-mass stars to be ejected out of the system on time-scales of interest (in contrast to the protoplanetary disc case).

4.3 Carving out an inner hole?

If stars embedded inside the disc eat it away before the gas can reach the SMBH, then the disc inner region may in principle be almost empty and hence underluminous compared with the steady-state standard accretion disc. This could then explain the observed lack of the BBB in the LLAGN spectra, interpreted as an inner hole in the accretion disc (e.g. Quataert et al. 1999).

We test this idea by comparing the expected disc spectra to the observations of M81 as an example. Given the quality of the data, we model the SED of cold discs consumed by the stars with a very simple model. We use the standard multitemperature blackbody spectrum with the exception that the accretion rate, $\dot{M}(R)$, is a function of radius. We neglect stellar irradiation compared with internal disc viscous heating. The local disc effective temperature is then given by equation (12).

We assume that stars are only present at radii larger than a 'self-gravity' radius, $R_{\rm sg}$. The latter may be smaller than $R_{Q=1}$ because of the possible radial migration of stars. For simplicity, we choose $\dot{m}(R) = \dot{m}(R_{\rm out})(R/R_{\rm out})^p$, for $R_{\rm sg} < R < R_{\rm out}$, and $\dot{m}(R) = \dot{m}(R_{\rm sg})$ for $R < R_{\rm sg}$. Fig. 2 shows the same data as Fig. 1 with several models for the disc emission. The solid line shows the alternative cut-off disc model similar to Quataert et al. (1999) – the standard accretion disc with the inner radius of $R_{\rm i} = 100 R_{\rm S}$ and the disc accretion rate $\dot{m}(R_{\rm out}) = 4 \times 10^{-3}$. The cold flow is presumed to evaporate and not to emit in the optical/UV region for $R < R_{\rm i}$. The dotted line shows the model with $p = 1$, $R_{\rm sg} = 100 R_{\rm S}$, $R_{\rm out} = 10^5 R_{\rm S}$ and $\dot{m} = 4 \times 10^{-3}$. Because for $p = 1$ the energy emitted per decade in radius ($\propto G M_{\rm BH} \dot{M}(R)/R^3 \times \pi R^2$) becomes independent of radius, there is a flat part in the infrared frequency part ($\nu \sim 10^{13}$–10^{14} Hz) of the spectrum for this model. The model is too dim in the optical/UV. The dashed line shows a similar model but with $R_{\rm sg} = 10^3 R_{\rm S}$. The model is clearly incompatible with the data.

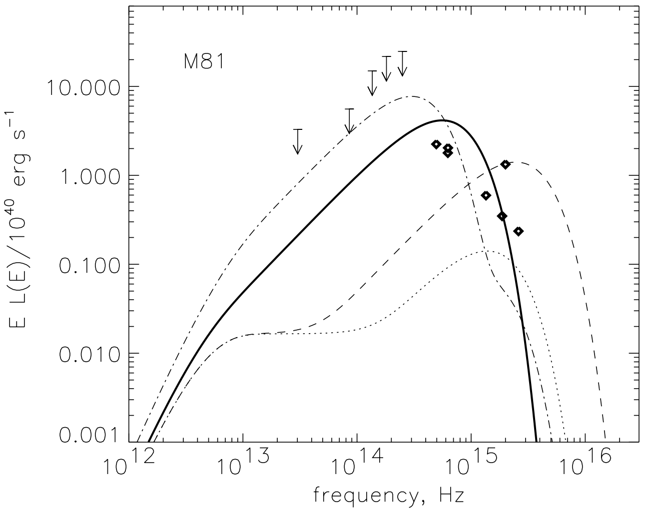

Figure 2. Modified cold disc fits to M81 infrared to UV SED. The standard disc with the inner cut-off radius of $100 R_{\rm S}$ is shown with the thick solid curve (Quataert et al. 1999, model). The rest of the curves assume cold inner disc persisting to the last stable orbit but the accretion rate decreases with radius as prescribed (see text for detail).

Finally, the dot-dashed curve shows a more complex model with $\dot{m} = \mathrm{const} = 3 \times 10^{-2}$ for $500 R_{\rm S} = R_{\rm sg} < R < R_{\rm out}$, $\dot{m} = \dot{m}(R_{\rm sg})(R/R_{\rm sg})^6$ for $100 R_{\rm S} < R < R_{\rm sg}$, and $\dot{m}(R) = \dot{m}(R_{\rm sg})$ for $R < R_{\rm sg}$. $R_{\rm out} = 10^5 R_{\rm S}$ in the model. This model roughly 'fits' the data. However, it is clearly fine-tuned to have a similar inner radius of $100 R_{\rm S}$ as the model of Quataert et al. (1999). The 'eaten-from-within' disc model may fit the data only if the accretion rate at the region $R \sim$ a few hundred $R_{\rm S}$ is similar to the cut-off disc model, and then drops very sharply. (What happens at larger radii is not that important as long as the outer disc is not too luminous in the infrared region.) A sudden disc depletion at a small range of radii is not impossible if there is a large concentration of low-mass stars there, but it seems a rather unlikely case to us. The total mass of the stars in this disc depletion region would not be very large, $\delta M_* \sim \dot{M}(R_{\rm out}) t \simeq 10^3\ \mathrm{M}_\odot (t/10^7\ \mathrm{yr})$ for $\dot{m} = 4 \times 10^{-3}$. However, the radial size of the $100 R_{\rm S}$ region is only $\sim 10^{14}$ cm $= 3 \times 10^{-5}$ pc, for the M81 SMBH mass, yielding a stellar density of the order of $3 \times 10^{16}\ \mathrm{M}_\odot\ \mathrm{pc}^{-3}$. Any star present at such small radii from a pre-existent isotropic cluster would have been destroyed in only $\sim$3 yr. The resulting disintegration of the stars would have resulted in a very energetic accretion event. Thus, this picture would mandate periods of quiescence when stars steal most of the mass from the accreting flow, and shorter periods of strong accretion activity on to the SMBH when the stellar collisions or supernova explosions (if stars grow to be too massive) release the stored gas. As the time between these luminosity variations is long compared to the history of astronomy, it is not immediately clear whether such a model is supported by observations or not.

4.4 Gap accretion. Clogging accretion flow with embedded stars?

For higher stellar mass to the SMBH mass ratios, gap formation occurs (see equations 7 and 8). The accretion rate of the star is reduced by the gap presence, but does not stop completely (e.g. Bate et al. 2003). When the mass of the star is small compared to the surrounding disc, the radial motion of the star is similar to that of the fluid at the same position in the disc. The star thus migrates closer to the SMBH on the disc viscous time-scale. Because of its small mass, the star does not significantly alter the radial surface density profile of the disc (Lin & Papaloizou 1986b). While the detailed disc spectrum may be affected by the presence of the star, the effect is quite minor as long as the star's mass is small compared to that of the disc, and the disc is optically thick.

However, when the mass of the star (or any massive satellite such as a secondary black hole) is considerable, the accretion disc is bound to 'notice' the satellite (Syer & Clarke 1995). Because the angular momentum exchange continues through the gap, the disc interior to the star is able to continue accretion on to the SMBH. At the same time, the gas at radii larger than the position of the star is blocked by the gap. Because of the high inertia of the star, the radial velocity of the gas just outside the gap is smaller than its unperturbed (i.e. star-free) value, and the disc surface density builds up there (Lin & Papaloizou 1986b; Syer et al. 1991; Ivanov, Papaloizou & Polnarev 1999). Syer & Clarke (1995) show that the radial migration velocity of the satellite becomes

$$v_{\rm s} = v_{\rm R,d} \frac{2\pi \Sigma R^2}{M_*}, \tag{15}$$

where $v_{\rm R,d} = 3\,\alpha (H/R)^2 v_{\rm K}(R)$ is the disc unperturbed radial viscous velocity. If $M_* \gg \pi \Sigma R^2$, the disc accretion is basically temporarily stopped, until the mass behind the satellite becomes large enough to push it through into the black hole. Meanwhile, the inner disc, cut off from the mass supply, empties out and may become quite dim (Syer & Clarke 1995). This situation will persist for a time $t \sim M_*/\dot{M} \sim 10^3\, m_* M_8^{-1} \dot{m}_{-3}^{-1}$ yr. This is actually an upper limit, because the overflow of the gap may occur at lower values of Σ, i.e. at somewhat earlier times. After enough mass has been accumulated, the accretion resumes, resulting in a bright outburst. The star and the built-up disc accrete on to the SMBH on the disc viscous time-scale, the one that reflects the amount of the stored mass. If the accretion rate in such an outburst is high enough, the inner disc becomes radiation-pressure dominated and the viscous time may be significantly shorter than that of the quiescent disc at the same location (this is due to a change in the factor $(H/R)^2$). The activity phase is thus relatively short compared with the mass accumulation phase.

Are such blocked accretion flows relevant to the apparently cut-off discs of LLAGNs? If this were the case, the LLAGN activity would be periodic, with the LLAGN being the quiescent state and a more brighter phase, such as Seyfert galaxies nuclei, would be the outburst state. The mass of the unperturbed accretion disc, estimated as $M_{\rm d} \sim \pi R^2 \Sigma(R)$ in the standard accretion flow is

$$M_{\rm d} = 60\,{\rm M}_{\odot} \alpha^{-4/5} M_8^{11/5} r_2^{7/5} \dot{m}_{-3}^{3/5}. \tag{16}$$

The disc is too heavy for a single star to induce serious accretion rate modulation for these parameters. For a smaller SMBH mass, say $4 \times 10^6\ {\rm M}_{\odot}$, the coefficient in equation (16) is about $0.05\ {\rm M}_{\odot}$, making a single star a big drag on to the accretion flow. The accretion luminosity can then be substantially modulated. Syer et al. (1991), considering the case of a 10^6-${\rm M}_{\odot}$ SMBH, already mentioned such a possibility. The quiescence time can be as long as 10^5 yr in this case.

Therefore, the possibility of a significant time variability due to presence of stars in the disc, and the 'empty' observational appearance of the inner disc, cannot be ruled out for lower-mass black holes. However, the absence of the UV bump (BBB) in the LLAGN spectrum is quite a general feature, seemingly independent of the SMBH mass. Indeed, many of the objects in the Ho (1999) sample have SMBH masses higher than $10^8\ {\rm M}_{\odot}$. The recent observations of Ptak et al. (2004) of NGC 3998, a LLAGN with the SMBH estimated at $\sim 10^9\ {\rm M}_{\odot}$, also show no clear BBB. Many stars embedded in the accretion flow and all drifting together could slow down the accretion in the inner regions of high SMBH accretion discs, but one would naively expect the stars to be smoothly distributed in the disc. Hence, embedded stars cannot explain cut-off discs in high-mass LLAGNs. Therefore, clogging up the disc flow with embedded stars is possible, but it cannot be the reason behind the missing inner accretion disc of LLAGNs.

5 STARS AT HIGH INCLINATION ANGLES TO THE DISC

So far we have been concerned with stars embedded in the disc. In general, however, there will be stars on highly inclined (to the disc) orbits, brought in by relaxation of the old central star cluster (e.g. Bahcall & Wolf 1976), or from partial capture of stars by the accretion disc (Syer et al. 1991), etc. If stellar orbital planes and the disc plane are significantly misaligned, then most of the interactions take place when the stars hit the disc and pass through it (e.g. Norman & Silk 1983; Ostriker 1983; Perry & Williams 1993; Zentsova 1983; Nayakshin et al. 2004). The stars move through the disc at very high Mach numbers and produce strong shocks. Quite generally, the stars are expected to enhance (speed up) the accretion flow because of the additional angular momentum transfer mechanism (Ostriker 1983) and the extra heating. Thus, this effect works in the opposite direction to that discussed in Section 4.4.

For radii smaller than some value $R_{\rm i}$, the angular momentum transfer in the disc is dominated by star–disc collisions rather than by the internal disc viscosity. The value of $R_{\rm i}$ is a function of the number density of stars in the inner part of the stellar cusp and their orbits (see Nayakshin et al. 2004, for estimates for Sgr A* under the assumption of an isotropic stellar cusp). If the angular momentum transfer mediated by stars is very fast, then the surface column depth of the disc is much smaller (for the same $\dot{M} = 2\pi R \Sigma v_{\rm R} = {\rm const}$) than it is for the standard disc. If it becomes optically thin, the disc will be much hotter for the same accretion rate. In fact, if it is unable to cool, the disc switches to a hot accretion mode, opening up an inner hole in the optically thick geometrically thin disc.[4]

Due to interactions with the disc, embedded stars have Keplerian circular velocities. If two such stars meet in the disc, their relative velocity is small. In contrast, stars out of the plane are expected to have a broad velocity distribution (e.g. Bahcall & Wolf 1976) and are prone to self-destruction in hard collisions (e.g. see section 3 of Murthy et al. 1991, and references therein). Such a collision may

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[4] Interestingly, this remark is also relevant to accretion discs around stellar-mass compact objects interacting with a cloud of comets – see Pineault & Landry 1994, and references therein.

involve two highly inclined stars or one star embedded in the disc and the other at a highly inclined orbit. If such an event occurs in the inner disc region, and especially if the mass of the inner disc is not too much greater than the combined mass of the two stars, then the resulting energy release will be sufficient to significantly speed up the accretion of the inner disc. The inner disc may then be quickly emptied out, and while it is being refilled the disc will radiate as a cut-off disc.[5]

Like the effects discussed in Section 4.4, these two mechanisms for the inner disc removal are also of a temporary nature. Unless being flat as an accretion disc, the inner stellar cusp will self-destruct by binary collisions in a relatively short time, e.g. 10^7–10^8 yr for typical cluster parameters (see, for example, fig. 6 of Murthy et al. 1991). Hence these mechanisms for the inner disc removal can be relevant to LLAGNs only if these are relatively short-lived phenomena in the SMBH/AGN activity cycles.

6 DISCUSSION AND CONCLUSIONS

Here we have suggested that close stars ($R \ll 1$ pc from the SMBH), created in the accretion disc by self-gravity in the bright quasar phase, may be present in the LLAGN discs. We have found (Section 3) that it is unlikely that these disc stars significantly contribute to the LLAGN optical/UV spectrum directly. Hot young massive stars are ruled out because most LLAGNs are weak in the UV; and low-mass stars would have to be too numerous. Stellar contribution in the infrared range is plausible, however, because the SEDs of standard accretion discs are weak in that region.

The effects of star mass, i.e. inertia, are much more realistic because they require a ‘small’ number of low-mass stars embedded in the disc (say 10^2 –10^4 stars). These stars can consume the disc faster than it can accrete on the SMBH (if no radial gap forms in the disc). In this case, little gas may be flowing into the central SMBH. However, when fitting the optical/UV spectrum of a ‘typical’ LLAGN, M81, we found that this model would only work if the disc were quickly and abruptly consumed by the embedded stars in the inner $\sim$ few hundred Schwarzschild radii. Further work is needed to determine whether this is natural and may be sustained for long enough times to explain the LLAGN phenomenon.

If a radial gap does form, then stars embedded in the disc accrete the gas from the disc much more slowly. However, their presence will still be felt by the disc if the disc mass interior to the star is smaller than the mass of the star (or group of stars). This appears to be especially important in the quiescent phase of limit-cycle unstable discs, in which case the stars will clog up the inner accretion flow for a time necessary for accumulation of enough disc matter to push the star in the disc. Because the disc interior to the star's location is quickly emptied out (Syer & Clarke 1995), such a star-terminated disc would appear as a cut-off disc. Finally, we have noted that hard stellar collisions in the inner disc region may disrupt the disc – create temporary inner holes.

We notice, however, that it is unlikely that the star–disc interactions discussed in this paper are the only explanation to the LLAGN ‘inner holes’ in the accretion disc. As we have seen in Section 4.4, the character of star–disc interactions depends strongly on the mass of the SMBH. Observations span a very large range in the SMBH mass, i.e. almost 10^3 (see, for example, Ho 1999; Ptak et al. 2004). Moreover, the accreting (stellar mass) binary systems may have inner holes in their accretion discs in the low-luminosity states as well (e.g. see Esin, McClintock & Narayan 1997; McClintock et al. 2003). Therefore, the star–disc interactions may be an additional reason for a complicated time variability in a disc that is already unstable (e.g. Lin & Shields 1986; Siemiginowska et al. 1996) or time-dependent because of a changing supply of fuel at large distances, but they are unlikely to be the primary reason for such variations in the disc structure.

Nevertheless, with observations becoming progressively better, we should expect many surprises, especially exotic variability, from the effects of star–disc interactions.

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[5] Because the duration of the event is very short compared with disc viscous time at large radii, the outer disc could be taken out of quiescence by the resulting illumination only in very limited circumstances: namely, when the outer disc is already close to being completely ‘filled’ and is ready for another outburst cycle.

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