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Stellar processes near AGN

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Abstract. Precise mechanisms by which Active Galactic Nuclei (AGN) receive their gaseous fuel is still a mystery. Here I draw attention to the extra ordinary star formation event that took place in the central ~ 0.5 parsec of our Galaxy. The most reliable explanation of the event seems to be that two somewhat massive nearly co-eval gaseous disks failed to accrete on Sgr A*, the super-massive black hole (SMBH) in our Galaxy, and instead cooled down and gravitationally collapsed, forming the stars observed now. This emphasises that star formation must be an important part of AGN feeding puzzle. I also discuss a model in which stellar winds create the observed obscuration of AGN. These winds are cold, clumpy and dusty, as required by the observations, but they are Compton-thin unless wind outflow rate is highly super-Eddington. This argument is in fact a general one, independent of the wind driving mechanism. I thus suggest that winds may be important for optically thin absorbers, and that a better model for optically thick AGN obscuration is a warped accretion/star forming disk.

1. Introduction

In X-ray binary systems, we know quite well the origin and properties of gas arriving at the outer edge of an accretion disk. In contrast to this, we know nothing for a fact about how gas trickles down into the inner parsecs of AGN. This is because observations of these regions are tremendously difficult: one needs to resolve very small angular scales faced at the same time with the contaminating emission from few tens of gravitational radii of SMBH. Despite all this, there is now a significant progress in such observations (Davies et al. 2006).

The Galactic Center (GC) is our most suitable laboratory for these studies due to its proximity and the fact that Sgr A* is in fact a very dim source, producing bolometrically only $\sim$ hundreds of Solar luminosities. As a result, young massive "He-I" stars dominate the power output of the central parsec of our Galaxy. Many of these stars are now resolved to be located in a very well defined and rather thin stellar disc that rotates clockwise as seen on the sky (Levin & Beloborodov 1993; Genzel et al. 2003; Paumard et al. 2006). The rest of the stars can be arguably classified as a second more diffuse disc or a feature that rotates counter clock-wise (Genzel et al. 2003; Paumard et al. 2006; Lu et al. 2006).

Below I shall argue that the best interpretation of data on these young massive stars is star formation inside an accretion disk(s) that existed in the inner parsec just before the stars were born. I shall discuss some observational and theoretical issues pertaining to formation and mass spectrum of these stars.

I will also present results of numerical simulations of star formation in a massive gaseous disc around Sgr A*.

Using Sgr A* observations as a launch pad for a discussion on the state of gas arriving in the inner parsecs of AGN, I will then argue that in general AGN disks are star-forming as well. I will then present numerical simulations of stellar winds escaping from a stellar disc left by a star formation event. Such winds might provide some obscuration of AGN, as required by observations. The results of the simulations however show that such outflows are unable to provide Compton-thick obscuration unless winds carry significantly super-Eddington outflow rates. A simple analytical estimate shows that this result is general for any wind-driving mechanism. I thus argue that, while certainly present and important for the working and appearance of AGN, *outflows are not responsible for Compton-thick obscuration.* Instead, I propose that the role of the Compton-thick absorber is played by a geometrically thin but strongly warped accretion/star-formation disk. As an example, gravitational torques due to a non-spherical stellar potential are demonstrated to be effective in producing strongly warped gaseous discs.

2. Observational constraints on the young stars in Sgr A* neighbourhood

2.1. The in-situ origin of the stars

There is nearly a hundred early type stars in the central parsec of our GC (Paumard et al. 2006). Finding these young stars there, as close as ~ 0.03 pc away from a SMBH, was a real surprise. “Standard” models of star formation are not easily applicable here due to a huge tidal field of the central object at $R = 0.1$ pc distances from Sgr A*. The required gas density is $n_H > 10^{11}\mathrm{cm}^{-3}(R/0.1\mathrm{pc})^{-3}$, i.e., exceedingly large compared with gas densities in galactic molecular clouds.

It thus has been suggested that the stars may have been formed at a distance of tens of parsecs (Gerhard 2001), avoiding the need for the excessive gas density prior to star formation, in a massive star cluster. The cluster’s orbit would then decay through dynamical friction with the background stars. However, (Paumard et al. 2006) find a well defined outer edge of about $\simeq 0.5$ parsec to the observed distribution of young massive stars in the GC. This is difficult to understand if stars migrated into the inner parsec from outside, as the disrupted cluster should leave a trail of stars behind it.

If the cluster were very strongly mass-segregated, i.e., that massive stars were present only in its core, then the trail could be composed of low mass stars only. These stars could escape detection in the near infra-red. This model seems to be challenged by X-ray data. Recent calibration of X-ray properties of T Tauri stars by (Preibisch et al. 2005) revealed that they are very bright in X-rays, i.e. some three orders of magnitude brighter than they are on the main sequence. They would be observable even at high extinction regions such as the GC. These young stars also display giant X-ray flares, with some becoming as bright as $\sim 10^{33}$ erg s^{-1}. (Nayakshin & Sunyaev 2005) used these new X-ray results for young stars, and observations of the GC reported in (**?**), to show that the inner ~ 10 parsec could not be hiding more than 10^4 or so young low mass stars. This is insufficient: some $10^5 - 10^6$ Solar masses of young stellar mass is needed to make the cluster heavy enough for it to sink in during the short lifetime of the young massive stars.

2.2. Top-heavy mass spectrum of the in-situ star formation event

Because Sgr A* is so dim in X-rays, it turned out possible to push the X-ray constraints further. Baganoff et al. (2003) described the properties of the unresolved X-ray emission near Sgr A* in detail. Nayakshin & Sunyaev (2005) used these results to deduce that the area most densely populated by massive young stars, i.e., the inner $R \leq 0.2$ parsec could contain no more than $\sim 10^3$ Solar masses of low-mass YSO ($M < 3$ Solar mass). This is interesting since a factor of 10 or so more would be expected if the IMF were the "normal" galactic one, such as (Miller & Scalo 1979).

2.3. Total stellar mass created

An important question to ask is the total mass budget of the star formation event. The best age estimate for the young stars in the GC is $\sim 6 \pm 1$ million years and their combined mass is a few thousand Solar mass (Paumard et al. 2006). Due to the age of this stellar population, stars more massive than $\sim 50 - 60$ Solar masses seem to be absent. Due to the top-heavy nature of the mass spectrum of the young stars discussed above, it is then possible that the initial star formation event created a star cluster far more massive than the one we observe now.

(Nayakshin 2005; Nayakshin & Cuadra 2005) proposed a way to constrain the total stellar mass using observational constraints on stellar orbits. Suppose that the two stellar systems were created infinitely thin and flat, as they would be in the simplest self-gravitating disc scenario (see §3 below). With time, an isolated stellar disc will thicken due to internal N-body heating, and two stellar discs will warp each other due to their non-spherical gravitational potentials. Both of these effects are stronger the more massive the stellar discs are. Now, if the initial systems were not thin and flat, then the thickening and warping will be even quicker (e.g., Nayakshin et al. 2006). Therefore, demanding that the model orbital configuration fits two stellar planes no worse than the real stars do at the present moment, we can arrive at a constraint on the total mass of these discs. This yields the limit of around 10^4 solar masses for the total masses of each of the stellar discs.

3. Theoretical models

It has been known for a long time that massive accretion discs can be gravitationally unstable and form stars if they are able to cool efficiently (e.g., Paczynski 1978; Gammie 2001; Rice et al. 2005). In particular, the disc has to be both massive enough and be able to cool fast enough: Toomre parameter $Q \leq 1$, and $t_{\rm cool} < 3\Omega^{-1}$, where $\Omega = \sqrt{GM_{\rm BH}/R^3}$. Vertically integrated marginally star-forming disc models have been considered recently with application to Sgr A* in mind (Levin 2006; Nayakshin 2006). Pleasingly, these models have a number of features consistent with the observations. The inner edge of the self-gravitating region, i.e. the closest to Sgr A* the stars can be born in this scenario, is about 0.03 pc, consistent with the distribution of the disk-stars (Paumard et al. 2006). Further, the models predict that all the gaseous disk mass would go into building up stars. The stellar mass is then estimated to be at $\sim 10^4$ Solar masses, which is not inconsistent with the observations.

The issue of the top-heavy mass function is more interesting. The estimates for the fragmentation mass, $M_{\rm frag}$, i.e. the mass of the first bound fragments, are certainly below 0.1 Solar mass. Hence, if disk were to *promptly* collapse into clumps of mass of this order, one would expect low-mass stars to dominate the mass spectrum of collapsed objects. However, in reality, collapse of gas clumps may not be dynamical (as assumed by the simple model), but gradual, regulated by cooling and clump rotation. Further, the clumps will have sizes comparable to the dimensions of the "first cores", i.e. $R_{\rm clump} \sim 5$ AU. The clumps are actually likely to merge and grow by agglomeration (Levin 2006). Therefore one expects that $M_{\rm frag}$ is a strong under-estimate of the actual stellar mass. Further, Nayakshin (2006) noted that low-mass proto-stars born with $M \sim M_{\rm frag}$ may grow very massive by gas accretion if disc fragmentation is slow. In particular, stellar accretion luminosity, produced by newly born proto-stars, turns out to be sufficient to heat the disc up, increasing the Toomre Q-parameter of the disc above unity and hence making the disc stable to further fragmentation. Numerical simulations (see below) do bear this prediction out.

4. Numerical models of star-forming discs

We use the SPH/N-body code GADGET-2 (Springel 2005) to simulate the dynamics of stars and gas in the (Newtonian) gravitational field of Sgr A*. Details of our method will be reported in Nayakshin, Cuadra & Springel 2007. Radiative cooling of the disc is treated with a simple locally constant cooling time prescription, $t_{\rm cool} = \beta/\Omega$, where β is a constant of order unity.

Circular gas discs without feedback. Left panel of Figure 1 shows a snapshot of a run with $\beta = 3$ well into the non-linear stage, at time $t \approx 10^4$ years, when more than half of the gas was already turned into stars. The initial condition is a gas disc of mass 2×10^4 Solar mass in Keplerian circular rotation around Sgr A*, extending from 1" to 4" (1"$\approx$ 0.04 pc). The right panel shows the same simulation in a slightly earlier time but now zoomed into a smaller patch of the disk to emphasise the disk structure.

Star formation is fastest in the innermost region, where most of the gas is already depleted. At the end of the simulation essentially all the gas is turned into stars. Unlike "normal" star formation, feedback from massive stars will not be very effective in blowing the gas away via radiation pressure or winds as the stars are within the deep potential well due to Sgr A*. The stars thus steal the majority of SMBH's dinner.

Interestingly, gravitational heating generated by stars (scattering off each other and interacting with gas) is sufficient to heat the disc up above its pre-star-formation value, slowing down and even shutting off fragmentation at later times. The effect is more pronounced the longer the cooling time. Figure 2, left panel, shows fragmentation rate in Solar masses per year as a function of time for simulations that differ only by the cooling time parameter β, as labelled in

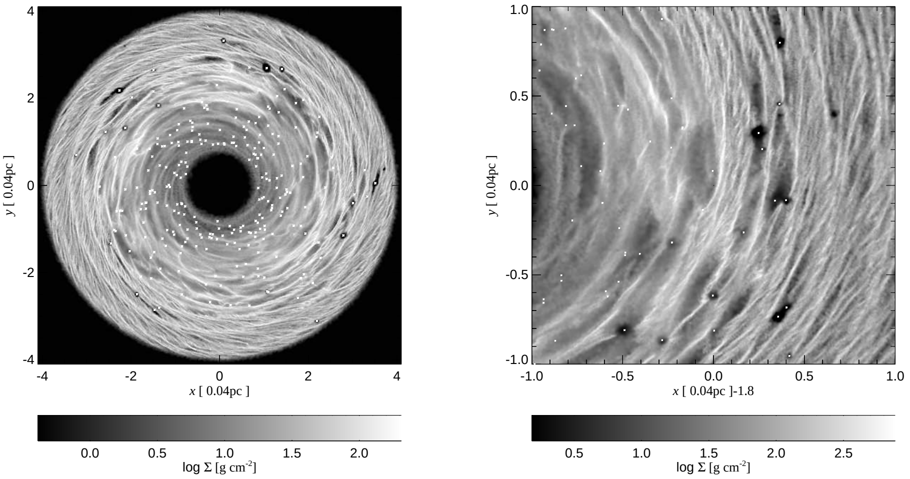

Figure 1. Left panel: Snapshot of a star-forming disc of initial mass 2×10^4 Solar masses at time $t = 10,000$ years. Stars are shown as asterisks. Right panel: Same shown for a small patch of the disk at time $t = 7,000$ years.

the caption. The longer the cooling time, the sooner disc fragmentation slows down and eventually stops as the disc becomes hotter. The total mass budget of the simulation is fixed by the initial condition. Quite logically then, the longer the cooling time the more top-heavy the mass function of the stars born in the simulation becomes. The IMF of the stars from these three simulations is presented in Figure 2, right panel.

The role of feedback on the fate of the discs and the IMF. As already mentioned, Nayakshin (2006) suggested that the accretion luminosity of young stars within a star-forming disk might be strong enough to warm it up and significantly slow down its fragmentation. We have made several numerical runs with stellar accretion feedback included. As expected, we found a very strong reduction in the fragmentation rate, and an increase in the disk lifetime defined as the time it takes for a half of its initial mass to be turned into stars. We could not reach a conclusive statement on the influence of the stellar accretion luminosity feedback onto the stellar mass function as the simulations could not be run sufficiently long.

The fact that disk lifetime increases strongly in the simulations is encouraging in terms of satisfying SMBH growth needs. If these results could be extrapolated into a much heavier accretion disc case, the time scale for angular momentum transfer mediated by self-gravity could become shorter than the disc lifetime. Unfortunately, this appears unlikely. In the simulations we used the simple β cooling time prescription. Quite a general analytical argument shows that, in order to feed AGN at rates of order Eddington accretion rates, the required levels of energy feedback from star formation (and in fact of any extra disc heating at all) are so large that they strongly contradicts the observed spectra of a typical AGN (Goodman 2003).

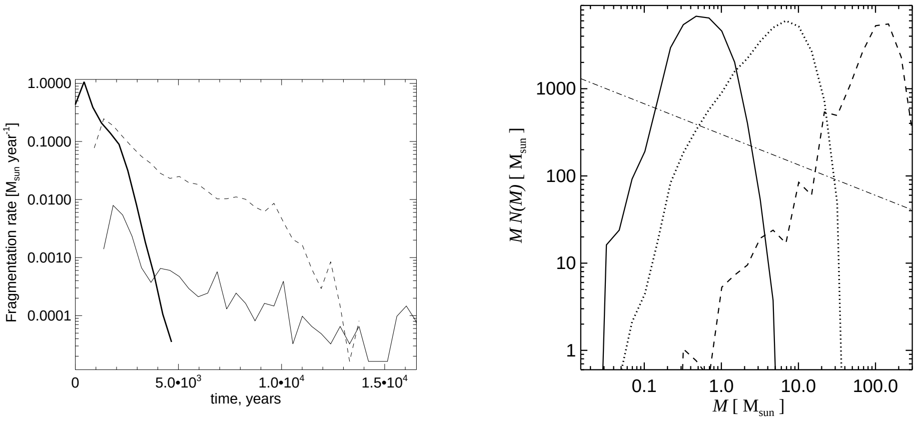

Figure 2. Left panel: Disc fragmentation rate in the tests with $\beta = 0.3$ (thick solid), $\beta = 2$ (dashed), and $\beta = 3$ (thin solid). The shorter the cooling time, the faster disc fragmentation proceeds. Right panel: Mass function of stars ("IMF") formed in the simulations with $\beta = 0.3$ (solid), $\beta = 2$ (dotted), and $\beta = 3$ (dashed). The dot-dashed power-law is the Salpeter IMF.

Star formation in eccentric discs The second of the observed stellar discs in the inner parsec of our Galaxy is a not so well defined diffuse feature with stellar orbits that appear to be rather eccentric ($e \sim 0.5 - 0.8$ Paumard et al. 2006). Since N-body relaxation time scale is about a Gyr, these stars must have been born on already eccentric orbits. We performed a series of tests aiming at establishing whether star formation can take place in eccentric discs. The results are rather similar to the runs with circular gas discs.

We think that the best case scenario for the GC stellar populations is one where the clock-wise disc stars formed out of a more massive circular gaseous disc, whereas the counter clockwise stars were born out of an eccentric stream of gas. Orbital precession could then turn an initially flat eccentric disc into a geometrically thicker one by now.

5. Star-forming winds and AGN obscuration

The talk by Moshe Elitzur (Elitzur 2006) summarises the observational need for a dusty AGN absorber and reviews important theoretical issues in that topic. It is proposed that a dusty clumpy outflow might be the best theoretical explanation for the absorber. Here I discuss related ideas. In particular, star formation on sub-parsec scales, discussed in previous sections of this paper, will naturally lead to stellar outflows. Provided the mass outflow rate is large enough, winds will be dense and thus cold, and quite likely dust-rich. In this case one might expect these outflows to play an important role in the obscuration of AGN.

SPH numerical modelling of stellar wind accretion on Sgr A* was recently developed by us (Cuadra et al. 2005,2006). Nayakshin & Cuadra (2007) used that numerical approach to model stellar wind obscuration, concentrating on higher mass outflow rates than in Sgr A* presently, as that might be expected in a bright AGN environment.

In the simulation presented here, stellar mass loss rates are 2.5×10^{-4} Solar mass year^{-1} per star. In total, we have 200 mass shredding stars, thus amounting to the mass loss rate of 0.1 Solar mass per year, which is a factor of few super-Eddington for Sgr A* mass of $M = 3.5 \times 10^6$ Solar mass. The stars are situated in a flat circularly rotating Keplerian disk of geometrical thickness $H(R) = 0.1R$, where R is the radius[1]. The disc inner and outer radii are $R_{\rm in} = 1.5$ and $R_{\rm out} = 8$, respectively.

A snapshot of the simulation is shown in Figure 3 at time $t \approx 2200$ years after the beginning of the simulation. While there is no true steady state for a system of a finite number of moving stars, the snapshot is fairly typical of the morphology of the stellar wind. The face-on view (left panel) shows that some of the shocked wind managed to cool down and formed a small-scale disc. Smaller escape velocity and less frequent shocks at the larger radii allow direct escape of both the fast diffuse and the slower cooler clumpy winds. Due to the final extent of the stellar disc and a projection effect, the wind morphology reminds an "X"-shape (Fig. 3, right panel).

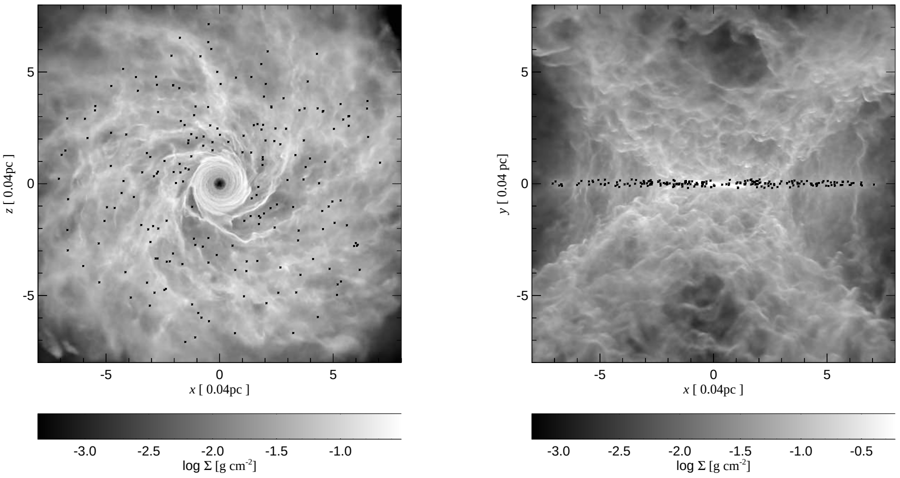

Figure 3. Face-on (left panel) and edge-on (right panel) views of the simulation domain for the flat stellar disc configuration. Black asterisks show the location of the wind-producing stars used in the simulation. From Nayakshin & Cuadra (2007)

The focus of our attention here is on the obscuration properties of these winds, and not on that of gaseous discs. The left panel of Figure 4 shows the obscuring column depth of the winds as seen from the SMBH, excluding the gas with radial distances $R < 1.6$ from Sgr A*, which removes most of the gaseous disc. Notice the very irregular patchy structure of the (brighter) optically thicker

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[1] The unit of length used here is 1 arcsecond, which corresponds to about 1.2×10^{17} cm or 0.04 pc at the Galactic Centre distance of 8 kpc.

regions. The contrast between those and neighbouring less dense patches of sky is frequently a factor of 10 or more. The dotted pattern at the $\cos\theta = 0$ plane are the dense regions of stellar winds immediately next to the stars.

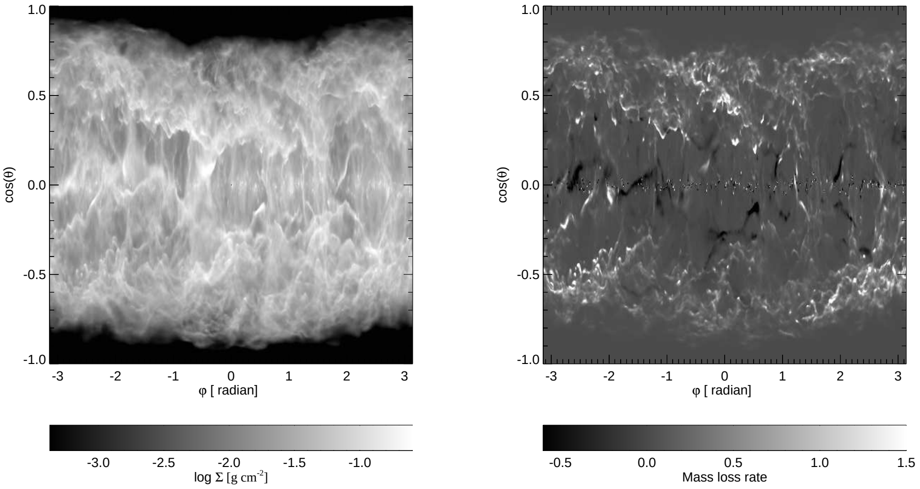

Figure 4. Column depth through the wind (left) and isotropic mass outflow rate (right; in units of Solar mass year^{-1}) for the simulation shown in Fig. 3, as seen from the SMBH. Note the large variations of the obscuring column depth over small angular scales. The gaseous inner disc seen in the left panel of Fig. 3 has been excluded.

The right panel of Figure 4 shows the isotropic mass loss rate along the line of sight, defined as

$$\dot{M} \equiv \frac{\int d\Sigma \; 4\pi r^2 \rho v_R}{\int d\Sigma} \; , \tag{1}$$

where the integral is taken along the line of sight defined by a given θ and ϕ.

Now, while the obscuration pattern in the left panel of Figure 4 may certainly be relevant to the observational need for a cold dusty absorber, there appears to be a serious limitation for this model. The average column depth is not large enough, i.e. it is Compton-thin. However, observations require a large fraction of AGN to be Compton-thick (e.g., Sazonov & Revnivtsev 2004; Guainazzi et al. 2005). To satisfy this requirement, the mass outflow rate, already super-Eddington by a factor of ~ 3, needs to be pushed another factor of > 5 higher.

This is an entirely general point. Considering clouds with average column depth $\Sigma_{\rm c}$ outflowing at speeds about the escape velocity, and numbering $N_{\rm a}$ per line of sight on average, one arrives (Nayakshin & Cuadra 2007) at the mass outflow rate of

$$\dot{M}_{\rm wind} \sim 15 \frac{M_\odot}{\rm year} \; N_{\rm a}\Sigma_{\rm c} \left(\frac{r_{\rm t}}{1 \; \rm pc}\right)^{1/2} M_8^{1/2} \; , \tag{2}$$

where M_8 is the SMBH mass in units of $10^8 M_\odot$, and r_t is the "torus size". Now, the Eddington accretion rate is $4\pi G M m_{\rm p}/\epsilon c \sigma_{\rm T} \approx 2 M_\odot {\rm year}^{-1} M_8$. The outflow is Compton-thick when $N_{\rm a}\Sigma_{\rm c} \geq 1$. Thus the required wind mass loss rate (equation 2) is an order of magnitude higher, typically, than the Eddington accretion rate for a $M_8 \sim 1$ object and a parsec-scale torus.

Considering a specific case of the local obscured AGNs studied by Guainazzi et. al. (2005), we note that the bolometric luminosities of these objects in the infrared, X-ray and optical bands are in the range $L \sim 10^{43}$ – few $\times\, 10^{44}$ erg/sec, which implies SMBH accretion rates of "only" $\sim 0.01 M_{\odot}$ year^{-1} for the standard radiative efficiency. Hence if the obscuration of the optically thick objects in that sample were provided by the winds, we would conclude that the SMBH accretion process must be very wasteful, with $\sim 100 - 10,000$ times more mass flowing out of the inner parsec than accreting on the SMBH. It would also require a very high mass influx into the inner parsec to sustain such winds. Given the difficulty of delivering enough fuel to the SMBHs even in the earlier gas-rich epochs, it is hard to see how such high mass in-fluxes could be maintained in the local AGN.

6. Warped accretion disc as an effective absorber

Given unrealistically high mass outflow rates required to obscure AGN in the wind outflow model, I suggest that outflows, while certainly being important for obscuration in optically thin AGN, do not nevertheless provide the bulk of the obscuration that must be optically thick. This is not to say that winds are not important for AGN physics!

I argue that a better physically motivated model for the absorber would be a warped accretion disc. The disc may be significantly warped by instabilities due to back reaction to mass outflow, or due to the AGN radiation pressure (e.g. Schandl & Meyer 1994; Pringle 1996). Nayakshin (2005) showed that an initially flat accretion disc can be quickly warped due to precession in a non-axisymmetric gravitational potential. The potential considered there was that of a stellar ring inclined with respect to the gaseous disc, a situation which probably existed in the Galactic Centre (Nayakshin & Cuadra 2005; Paumard et al. 2006). Finally, there is in general no reason for an initial disc configuration to be flat (Phinney 1989).

7. Summary and Conclusions

In this article I considered some manifestations of stellar activity in the inner parsecs of galaxies, inside of what is usually considered to be an AGN accretion disc domain. Stars are important sinks of mass during star formation and are important radiation and matter sources later on when stars start to burn their nuclear fuel. Observations of our Galactic Center highlight the problem faced by accretion disc models on ≥ 0.1 pc scales. Accretion discs are very cold there, and one expects these discs to be making stars rather than accreting. This appears to be exactly what happened with two ring/disks of gas in the inner ~ 0.5 pc of our galaxy about 6 million years ago. If not for the star formation, Sgr A* could be a respectable low-luminosity AGN now (Nayakshin & Cuadra 2005). It seems indisputable that a working solution of the AGN/quasar feeding problem will have to include star formation as well. Much theoretical work remains to be done in this area.

I also considered the possible role of outflows driven away by stars populating star forming discs like those observed in Sgr A*. It is found that these winds are clumpy, cold and may well contain dust, as required by the "torus" outflow model of Elitzur & Shlosman (2006). This model thus might work well for Compton-thin sources. The outflows become optically thick when they are powered by mass loss rates a factor of ∼ 10 or more larger than the mass accretion rate corresponding to Eddington Luminosity for the AGN. This appears to be a general problem for obscuration by any kind of an outflow. I propose that warped accretion disks can provide the needed optically thick AGN obscuration.

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