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ACCRETION ONTO A SUPERMASSIVE BLACK HOLE LOCATED IN THE CENTER OF A YOUNG STAR FORMING REGION

Spherically symmetric accretion onto a supermassive black hole located in the center of a young star forming region is discussed. It is shown that the negative feedback provided by massive stars prevents the accretion of the ambient interstellar gas onto the central black hole and leads to a bimodal solution which is qualitatively different from the classic Bondi results. In this case the central supermassive black hole accretes only a small fraction of matter returned by massive stars located in the nuclear zone of the host galaxy, which results in low Eddington ratios similar to those observed in low-luminosity active galactic nuclei. In the starburst dominated accretion solution, parameters of the central starburst instead of parameters of the ambient interstellar medium determine the mass accretion rate and the central black hole luminosity. The starburst dominated accretion model also predicts the delay between the onset of the starburst event and the time when the black hole activity reaches its maximum value.

Keywords: active galaxies, supermassive black holes, starburst.

1. Introduction

It is a common believe that supermassive black holes (SMBHs) are hidden in the centers of essentially all present-day galaxies. However the majority of SMBHs in the local universe are radiatively dim. Their 2 keV – 10 keV luminosities do not exceed $\sim 10^{40}$ erg s^{-1} (Pellegrini 2005; Soria et al. 2006; Ho 2009; Volonteri et al. 2011; Wong et al. 2011) and do not display clear relation with the expected Bondi accretion rate (Pelegrini 2005; Soria et al. 2006; Wong et al. 2011). In terms of the Eddington ratio $\eta_E = L_{BH} / L_{Edd}$, the SMBHs sometimes as week as $10^{-7} - 10^{-8}$ (Yuan et al. 2003; Soria et al. 2006; Ho 2009). Fabian & Rees (1995) stressed long time ago that this problem is more general than just a low luminosity detected in a few special objects and that the radiatively inefficient SMBHs represent one of the most intriguing aspects of the accretion phenomenon.

It is also well known that in many cases galaxies with a central SMBH contain a young stellar population and that nuclear starbursts are often associated with low luminosity AGNs (Davies et al 2007; Watabe et al. 2008; Chen, 2009; Esquej et al. 2014, see also a review by Heckmann & Best 2014). The overall conclusion from these and many other studies is that in up to 50 % of the cases the SMBHs are embedded into a young star forming region with an age less than a few hundreds of Myrs.

On the galactic scale no clear correlation between the SMBH activity and the host galaxy star formation rate has been found. However Chandra observations of the inner zone of the Milky Way galaxy revealed a diffuse X-ray emission which is likely originates from the interaction of powerful stellar winds generated by massive stars located in the young nuclear stellar cluster (Baganoff et al. 2003). The near infrared observations with a high spatial resolution provided with the integral field spectrograph SINFONI also revealed compact (tens of parsecs) recent (10Myr - 300Myr) short lived starbursts in the nuclear zones of the nearby Seyfert galaxies (Davies et al. 2007). Analysis of these observations indicates on a delay of 50 - 100 Myr between the onset of the central starburst and the subsequent activity of the central SMBH (Davies et al. 2007

Wild et al. 2010). Following on mid-infrared $8\mu - 13\mu$ observations by Ramos Almeida et al. (2013) also revealed nuclear starbursts with star formation rates (SFRs) in the range $0.01M_e yr^{-1} - 1.2M_e yr^{-1}$ in a sample of 29 Seyfert galaxies selected from the Revised Shapley-Ames catalog. In some cases such pc-sized starbursts coincide with low luminosity AGNs as in the case of NGC 4303 (Colina et al. 2002; Jimenez-Bailon et al. 2003) and NGC 1097 (Storchi-Bergmann et al. 2005).

Two major solutions for the low luminosity active galactic nuclei (LLAGN) problem were discussed during the last decades. One is that in the low accretion rate flows most of the energy is advected down the radius of the SMBH horizon before being radiated away. This leads to the low accretion efficiently η which in the advection dominated accretion flows (ADAFs) may be much smaller than in the standard accretion disc model where $\eta = 0.1$ (see Narayan et al. 1998; Quataert 2001). However Bisnovatyi-Kogan & Lovelace (2000) stressed out that ADAF solution should be treated with caution because of its insufficient physics and claimed that electron heating due to the magnetic field reconnection may significantly restrict the applicability of this solution and lead to the radiative efficiency of about 25 % of the standard value.

Pellegrini (2005) estimated temperatures and densities of the interstellar gas in the circumnuclear regions of 18 nearby galaxies with a nuclear SMBH, calculated the Bondi accretion rates and compared them to the observed luminosities of the central BHs. He found that in a few cases the standard ADAF model indeed may explain the observed BH luminosities. However, in many galaxies the predicted BH luminosities are still too large when compared with observations. The complementary study of the nuclear X-ray emission in the other six quiescent early-type galaxies led Soria et al. (2006) to the similar conclusion.

Another approach to the problem is that not all in-falling matter reaches the event of horizon either due to convection (convective dominated accretion flows or CDAF solution, Narayan et al. 2000; Quataert & Gruzinov, 2000) or because some fraction of the in-flowing matter remains gravitationally unbound and escapes the gravitational well of the central BH (advection-dominated inflow-outflow solutions or ADIOS model; Blandford & Begelman, 1999).

Here I show that in the case when SMBH is located in the center of a young stellar cluster the ambient interstellar medium (ISM) cannot fuel the central SMBH due to the negative star formation feedback which prevents the in fall of the ambient interstellar gas on to the center. In this case the SMBH is fed by the gas reinserted by stars located in the nuclear zone of the host galaxy (see Figure 1) and the accretion rate is determined by the negative star formation feedback and by the amount of matter injected by stars within a nuclear star forming region (David et al. 1987; Quataert, 2004; Silich et al. 2008; Hueyotl-Zahuantitla et al. 2010).

2. Input physic

2.1. Stellar density distribution

For a nuclear starburst I adopt a truncated King stellar mass distribution (King 1972):

$$\rho_*(r) = \frac{\rho_{*0}}{[1 + (r / R_c)^2]^{3/2}} \tag{1}$$

where ρ_{*0} is the central stellar density and R_c is the radius of the stellar core. This distribution is truncated at some radius R_{SC} to have a finite stellar mass. The mass inclosed within a radius r then is:

$$M(r) = \int_0^r \frac{4\pi\rho_{*0}x^2}{[1+(x/R_c)^2]^{3/2}} = 4\pi\rho_{*0}R_c^3 I(r) = M_{SB} I(r)/I_T \qquad (2)$$

where M_{SB} is the total mass of the stellar cluster and R_c is the core radius which determines the characteristic length-scale for the stellar density distribution. Function $I(r)$ is:

$$I(r) = \ln\{r/R_c + [1+(r/R_c)^2]^{1/2}\} - r/R_c[1+(r/R_c)^2]^{-1/2} \qquad (3)$$

and $I_T = I(R_{SC})$

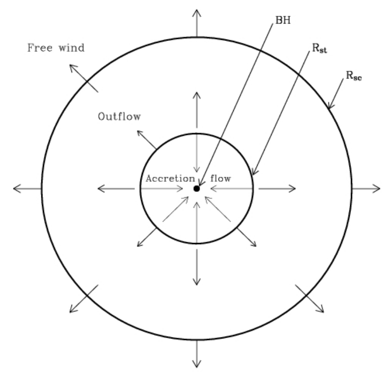

Fig. 1. A cartoon representation of the starburst dominated accretion flow. The inner and outer circles display stagnation radius, R_{st}, and the star cluster cut-off radius R_{SC}, respectively. The SMBH is located in the star cluster center. Arrows indicate the direction of the flow velocity inside and outside of the stagnation surface.

2.2. Energy and mass deposition rates

The stellar mass loss rate, the mechanical and radiative energy deposition rates are calculated by means of the Starburst99 synthetic model. It is assumed that the stellar mechanical (q_e) and radiative (q_r) energy input rates and the mass deposition rate q_m per unit volume scale with the stellar density distribution and are given by:

$$q_e(r) = q_{e0}[1+(r/R_c)^2]^{3/2}, \qquad q_{e0} = L_{mech}/4\pi R_c^3 I_T, \qquad (4)$$

$$q_r(r) = q_{r0}[1+(r/R_c)^2]^{3/2}, \qquad q_{r0} = L_{bol}/4\pi R_c^3 I_T, \qquad (5)$$

$$q_m(r) = q_{m0}[1+(r/R_c)^2]^{3/2}, \qquad q_{m0} = \dot{M}_{SB}/4\pi R_c^3 I_T \qquad (6)$$

where L_{mech} and L_{bol} are the starburst mechanical and bolometric luminosity, respectively, and $\dot{M}_{SB}$ is the stellar mass loss rate. If the star formation event is not instantaneous and the star formation rate (SFR) changes with time, the starburst parameters at a given evolutionary time t are calculated as a sequence of N_{tot} instantaneous starbursts separated by a $\Delta\tau = t_{max}/N_{tot}$ time intervals (e.g. Terlevich et al. 2004).

Each instantaneous starburst evolves independently according to its own clock set:

$$t_i = t - (i-1)\Delta\tau \tag{7}$$

and has mass

$$M_i = SFR_0 \int_{t_{i-1}}^{t_i} e^{t/\tau_{SB}} dt \tag{8}$$

where t is the evolutionary time and i is the instantaneous starburst number. One can obtain then the mechanical and bolometric luminosities and the mass deposition rate at any time t by adding the individual burst parameters obtained from the evolutionary synthesis model:

$$L_{mech}(t) = \sum_{i=1}^{i=n(t)} L_{i,mech} \, , \tag{9}$$

$$L_{bol}(t) = \sum_{i=1}^{i=n(t)} L_{i,bol} \, , \tag{10}$$

$$\dot{M}_{SB}(t) = \sum_{i=1}^{i=n(t)} \dot{M}_i \, . \tag{11}$$

The evolution of the mechanical luminosity L_{mech}, mass deposition rate $\dot{M}_{SB}$ and the bolometric luminosity L_{bol} of an exponentially decaying starburst with the characteristic time scale $\tau = 10\,\mathrm{Myr}$, total mass $M_{SB} = 10^7\,\mathrm{M_e}$ and the initial star formation rate $SFR_0 = 1\mathrm{M_e yr^{-1}}$ is shown in Figure 2.

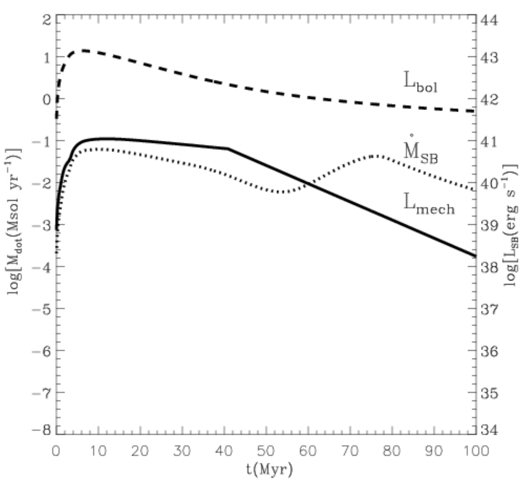

Fig. 2. Time evolution of the starburst parameters. The dotted, dashed and solid lines show the time evolution of the mass deposition rate, bolometric and mechanical luminosities of a $10^7\,\mathrm{M_e}$, starburst with an initial star formation rate $SFR_0 = 1\mathrm{M_e yr^{-1}}$ and the characteristic time-scale $\tau = 10\mathrm{Mir}$

3. Main equations

Gas heated in the random collisions of nearby stellar winds and supernovae explosions has a characteristic temperature $10^6 K$ - a few times $10^7 K$. The sound crossing time over a few tens of parsecs which is a typical size of a young nuclear star-forming region (Davies et al. 2007), then does not exceed a few times 10^5 years. This is much smaller than the characteristic time-scale for the starburst parameters evolution (see Figure 2). Therefore one can study the accretion flow on to a SMBH in the center of a young stellar system by making use a time-independent solution with input parameters depending on time. The hydrodynamic equations for the steady state, spherically symmetric flow driven by a starburst with a supermassive black hole in the center are (see, for example, David 1987; Silich et al. 2008):

$$\frac{1}{r^2}\frac{d}{dr}(\rho u r^2) = q_m , \tag{12}$$

$$\rho u \frac{du}{dr} = -\frac{dP}{dr} - q_m u - \frac{G\rho[M(r)+M_{BH}]}{r^2} + \frac{K_{Th}\rho}{c}\frac{L_{bol}(t)+L_{BH}}{4\pi r^2} , \tag{13}$$

$$\frac{1}{r^2}\frac{d}{dr}\left[\rho u^2 r\left(\frac{u^2}{2}+\frac{\gamma}{\gamma-1}\frac{P}{\rho}\right)\right] = q_{in} - Q - \frac{Gru[M(r)+M_{BH}]}{r^2} + \\ + \frac{K_{Th}\rho u}{c}\frac{L_{BH}+L_{bol}(r)+L_{cool}(r)}{4\pi r^2} \tag{14}$$

where u, P, and ρ are the flow velocity, thermal pressure and density, respectively, γ is the ratio of the specific heats, G is the gravitational constant, K_{Th} is the Thompson cross-section per unit mass, $M(r)$ and $L_{bol}(r)$ are the mass and the bolometric luminosity of the stars enclosed into a volume with radius r. M_{BH} and L_{BH} are the mass and the accretion luminosity of the central black hole. $q_{in}(r) = q_e(r) + q_s(r)$ is the mechanical energy input rate, $q_s(r)$ is the energy input due to the random motion of stars in the gravitational well of the cluster and the central black hole. $Q = n_e n_i \Lambda(T, Z)$ is the cooling rate, n_e and n_i are the electron and ion number densities and $\Lambda(T, Z)$ is the cooling function, which depends on the gas temperature T and metalicity Z.

The flow is always bimodal if the star forming region contains a supermassive black hole in the center. In this case the flow is split onto two zones by the stagnation radius R_{st} (see Figure 1). At $r = R_{st}$ the flow velocity is $0\,\mathrm{km\,s^{-1}}$. Outside of this radius the reinserted matter flows away as a wind, whereas inside it is captured by the gravitational field of the central SMBH and forms an accretion flow. Thus the amount of mass available for the accretion on to the central black and the SMBH luminosity in this solution are determined by the stagnation radius and have nothing to do with parameters of the ambient ISM.

4. Initial and boundary conditions

Taking into account that in the stagnation point $u = 0$, one can obtain the condition of radiative equilibrium which relates the density and the temperature in the stagnation point (e.g. David et al. 1987; Silich et al.2008):

$$n_{st} = q_{m0}^{1/2}\left[\frac{q_{in}/q_{m0} - \alpha_{st}^2/(\gamma-1)(1+R_{st}^2/R_c^2}{\Lambda_{st}}\right]^{1/2} . \tag{15}$$

One can also obtain the derivative of the flow velocity and that of the gas pressure in the stagnation point:

$$\frac{du}{dr} = \frac{1}{\rho}\frac{(\gamma-1)(q_{in}-Q)}{a^2} , \tag{16}$$

$$\frac{dP}{dr} = -\frac{G\rho[M_{BH} + M(r)]}{r^2} + \frac{K_{Th}\rho L_{tot}(r)}{c4\pi r^2}. \qquad (17)$$

Equations (15)-(17) allow one to determine all hydrodynamical variables at a small distance $r = R_{st} \pm \Delta r$ from the stagnation radius and start the outward and inward integrations of the hydrodynamic equations from the stagnation point. The shape of the integral curve is determined by the value of the stagnation radius R_{st} and by the stagnation temperature T_{st}. One can select then a unique integral curve that has a physical meaning from the infinite branch of solutions by making use the condition that it passes through the outer and inner singular points (David et al. 1987; Silich et al. 2008).A twofold iterations were performed to find this solution. I first choose a trial stagnation radius R_{st} and provide outward integrations with different stagnation temperatures until find a transonic wind solution in the outer part of the flow and then check if the selected values of R_{st} and T_{st} also result in the transonic accretion flow. Iterations stop when the integral curve passes through both, the inner and the outer singular points.

5. SMBH luminosity

Selecting the proper integral curve, one can obtain the value of the stagnation radius and thus the amount of matter available for the accretion and the luminosity of the central SMBH. The results of the calculations for two different $10^7\,M_\odot$ and $10^8\,M_\odot$ SMBHs embedded into a star forming region with $SFR_0 = 1\,M_e\,yr^{-1}$, characteristic time scale $\tau = 10\,Myr$, $R_c = 10\,pc$ and $R_{SC} = 100\,pc$, are shown in Figure 3. The left-hand panel in this figure displays the model-predicted SMBH luminosity and the bolometric luminosity of the central cluster. Here the solid, dashed and dotted lines display the accretion luminosity of a $10^7\,M_\odot$ and $10^8\,M_\odot$ black holes and the bolometric luminosity of the starburst, respectively. The right-hand panel in Figure 3 shows the same results in terms of the Eddington ratio.

The BH luminosity first drops reaching the minimum value at about $50\,Myr$ after the beginning of the starburst event. During this time the value of the stagnation radius does not change significantly, but the mass deposition rate decreases (see Figure 2) that reduces the amount of mass available for the accretion. After this time the SFR, the number of massive stars and thus the mechanical luminosity of the starburst drop rapidly. However the mass returned by stars does not change equally fast and between $50Myr$ and $80Myr$ even grows up (see Figure 2) due to massive winds of the AGB stars. This results in a fast growth of the stagnation radius and the accretion rate. The SMBH luminosity reaches the maximum value at about $80Myr$ after the beginning of the starburst event. The maximum in the BH activity maybe shifted even to a larger time in the case of slowly decaying starbursts with $\tau > 10Myr$. The accretion luminosity scales approximately as $L_{BH} \sim M_{BH}^2$ as it is also the case in the Bondi accretion model. However in the starburst dominated accretion regime the value of the accretion rate and the BH luminosity are determined by the intensity of the central starburstand do not depend on the density and temperature in the ambient interstellar medium as the Bondi model predicts.

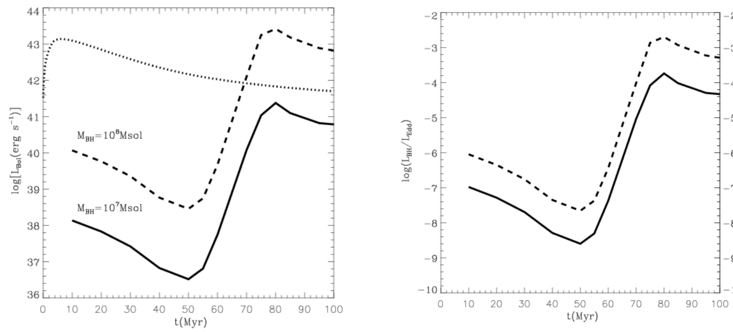

Fig. 3. The central BH luminosity as a function of time. The left-hand panel shows the luminosity of a SMBH located in the center of a $10^7 M_\odot$ star forming region and compare that to the bolometric luminosity of the starburst (dotted line). The right-hand panel shows the model predicted SMBH luminosity in terms of the Eddington ratio. The solid and dashed lines display the luminosity of a $10^7 M_\odot$ and $10^8 M_\odot$ black hole, respectively.

6. Concluding remarks

Here I discussed the interplay among the central SMBH and star formation in the central zone of the host galaxy. It was shown that the mass accretion rate and the central SMBH luminosity in this case are determined by the central starburst parameters, its time evolution and by the mass of the SMBH, but not by the ambient gas density and temperature as the classic Bondi model predicts. In all calculations the central SMBH luminosity remains rather small and at the initial stages of the central starburst evolution does not exceed the bolometric luminosity of the starburst. The calculated Eddington ratiofalls into the range $10^{-10} \le \eta_E \le 10^{-3}$ which is usually observed in LLAGNs (e.g. Yuan et al. 2003; Soria et al. 2006; Ho, 2009).The starburst dominated accretion solution also predicts a delay between the onset of the starburst event and the maximum BH activity as it is observe in some nearby Seyfert galaxies.

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