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SMBH feeding and star formation in massive accretion discs

L. Šubr[1,2]

[1] Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2, CZ-18000, Praha, Czech Republic
[2] Astronomical Institute, Academy of Sciences, Boční II, CZ-14131 Praha, Czech Republic
e-mail: subr@sirrah.troja.mff.cuni.cz

Abstract. Galactic nuclei are unique laboratories for the study of processes connected with the accretion of gas onto supermassive black holes. At the same time, they represent challenging environments from the point of view of stellar dynamics due to their extreme densities and masses involved. There is a growing evidence about the importance of the mutual interaction of stars with gas in galactic nuclei. Gas rich environment may lead to stellar formation which, on the other hand, may regulate accretion onto the central mass. Gas in the form of massive torus or accretion disc further influences stellar dynamics in the central parsec either via gravitational or hydrodynamical interaction. Eccentricity oscillations on one hand and energy dissipation on the other hand lead to increased rate of infall of stars into the supermassive black hole. Last, but not least, processes related to the stellar dynamics may be detectable with forthcoming gravitational waves detectors.

Key words. Accretion, accretion discs — stellar dynamics — Galaxy: center

1. Introduction

Standard model of active galactic nuclei consists of a supermassive black hole (SMBH) of mass $M_{\rm BH}$ surrounded by an accretion disc which extends to $\sim\ 10^4 - 10^5 R_{\rm g}$; $R_{\rm g} \equiv GM_{\rm BH}/c^2$. Further away, at $r \gtrsim 10^6 R_{\rm g}$, there is assumed to be an obscuring massive molecular torus. Within the radius of $\sim 10^6 - 10^7 R_{\rm g}$, there is a dense stellar cusp, of the total mass comparable to $M_{\rm BH}$. In spite of its extreme density which may exceed 10^8 stars per cubic parsec in the center, the two-body relaxation time in this region is of the order of Gyr. Hence, on the orbital (crossing) time scale, the stars follow nearly Keplerian orbits in the gravitational field of the SMBH. Interaction of stars with the axisymmetric gaseous structures leads to a secular orbit evolution. Its characteristic time may be well below the relaxation time and, therefore, it can lead to observable effects.

In this contribution we briefly introduce various modes of the mutual interaction of the stars and gas in galactic nuclei and discuss possible consequences. In Section 4 we present our results within the context of the nucleus of the Milky Way.

2. Gravitational interaction

Gravitational field of the SMBH as well as the mean field of the star cluster are assumed to be spherically symmetric, which implies conservation of the vector of the angular momentum.

This is no longer true once a non-spherical perturbation to the gravitational field is introduced. We will concentrate on the case of an additional component of the gravitational field due to the accretion disc or molecular torus for which we assume an axial symmetry. Then, one component of the angular momentum vector, L_z, parallel to the symmetry axis will be conserved, but the eccentricity may change.

This process, sometimes referred to as Kozai oscillations, is well described by means of the perturbation Hamiltonian theory for an analogical (reduced) hierarchical triple system (Kozai 1962; Lidov 1962). For the simplest case of perturbation potential due to an infinitesimally narrow ring of mass M_d and radius R_d, the equations of motion in the first approximation read:

$$T_\mathrm{K}\,\eta\,\frac{\mathrm{d}e}{\mathrm{d}t} = \frac{15}{8}\,e\,\eta^2\,\sin 2\omega\,\sin^2 i\,, \quad (1)$$

$$T_\mathrm{K}\,\eta\,\frac{\mathrm{d}i}{\mathrm{d}t} = -\frac{15}{8}\,e^2\,\sin 2\omega\,\sin i\,\cos i\,, \quad (2)$$

$$T_\mathrm{K}\,\eta\,\frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{3}{4}\left\{2\eta^2 + 5\sin^2\omega\left[e^2 - \sin^2 i\right]\right\}, \quad (3)$$

$$T_\mathrm{K}\,\eta\,\frac{\mathrm{d}\Omega}{\mathrm{d}t} = -\frac{3}{4}\cos i\left[1 + 4e^2 - 5e^2\cos^2\omega\right], \quad (4)$$

where a, e, i, ω and Ω are the mean orbital semi-major axis, eccentricity, inclination with respect to the plane of symmetry of the perturbing potential, argument of the pericenter and the longitude of the ascending node, respectively. We denote $\eta \equiv \sqrt{1-e^2}$ and

$$T_\mathrm{K} \equiv \frac{M_\mathrm{BH}}{M_\mathrm{d}}\,\frac{R_\mathrm{d}^3}{a\sqrt{GM_\mathrm{BH}a}}\,, \quad (5)$$

which is the characteristic time of the evolution of the orbital elements. Equations (1) – (3) have two integrals of motion,

$$C_1 = \eta\sin i \quad \text{and} \quad C_2 = (5\sin^2 i\sin^2\omega - 2)e^2, \quad (6)$$

which implies that three orbital elements, e, i and ω, change periodically with equal period and phase. For low values of C_1, the amplitude of the oscillations of eccentricity may, in terms of η, reach several orders of magnitude. Therefore, we expect enhanced rate of events connected with extreme eccentricities, e.g. tidal disruptions of stars.

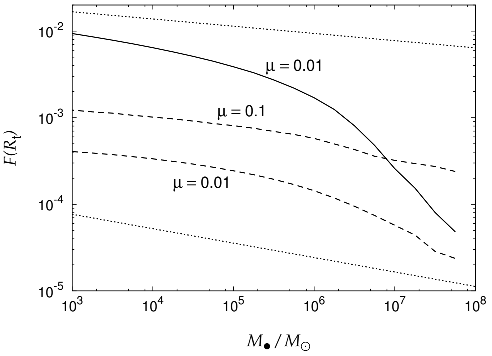

Fig. 1. Size of the loss cone of tidal disruptions as a fraction of the phase space. Lower dotted line represents size of the loss cone for an unperturbed case. Upper dotted line corresponds to an estimate for the case of perturbation due to the ring. Model represented by the solid line contains the 1.PN correction in addition. Dashed lines stand for complex models, including the gravity of the stellar cusp.

In the case of the galactic nuclei, there are, however, two additional perturbations to the dynamics of individual stars, that tend to diminish the amplitude of the eccentricity oscillations. It is the mean potential of the stellar cusp and the relativistic pericenter advance. For some sets of parameters, both of them lead to substantial increase of $|\mathrm{d}\omega/\mathrm{d}t|$, i.e. to the shortening of the period of the oscillations and also to damping of their amplitude (Blaes et al. 2002; Ivanov et al. 2005).

In Karas & Šubr (2007) we have compared the volume of the loss cone of the central star cluster occupied by stars that reach the SMBH within the tidal radius, R_t. We have considered a Bahcall & Wolf (1976) profile of the cusp and various disturbing components to the central Keplerian potential, i.e. the axially symmetric ring or disc, first post-Newtonian correction to the central potential and the spherically symmetric mean potential of the stellar cusp. The results are presented in Fig. 1. When considering only the ring as a perturbation, the loss cone is more than two orders of magnitude larger in comparison to the unperturbed case. Relativistic pericenter advance damps the Kozai oscillations for $a < a_\mathrm{t}$,

$$a_\mathrm{t}^7 \approx \tfrac{32}{9}\,R_\mathrm{d}^6\,R_\mathrm{g}^2\,R_\mathrm{t}^{-1}\,\mu^{-2}\,, \quad (7)$$

where we denote $\mu \equiv M_\mathrm{d}/M_\mathrm{BH}$. This transforms into the break of the solid line in Fig. 1 at $M_\mathrm{BH} \approx 10^6 M_\odot$. The pericenter shift caused by the stellar cusp, mass of which was set equal to M_BH in Fig. 1, leads to a systematic decrease of the loss cone over the whole range of the black hole mass. We may conclude that axisymmetric perturbation to the potential of the SMBH may increase the number of the tidally disrupted stars by a factor $\gtrsim 10$. This number may by further increased if the source of the axisymmetric component of the potential extends over a large range of radii (Karas & Šubr 2007).

3. Hydrodynamical interaction

The dynamical processes described in the previous Section do not (in the first approximation) change energy of individual stars. On the other hand, repetitive passages of the stars through the accretion disc lead to dissipation of their kinetic energy (Syer et al. 1991; Vokrouhlický & Karas 1998; Šubr & Karas 1999). Being highly supersonic, the dissipational efficiency of the star–disc collisions is assumed to be proportional to the physical cross-section of the star and the column density of the accretion flow. For a standard gas pressure dominated Shakura & Sunyaev (1973) accretion disc the characteristic time of the orbital decay can be estimated as (Šubr et al. 2004):

$$t_\mathrm{coll} \approx M_8 \left(\frac{\Sigma_*}{\Sigma_\odot}\right) \left(\frac{a}{R_\mathrm{g}}\right)^{9/4} \mathrm{yr}\,, \tag{8}$$

where $\Sigma_* \equiv M_*/R_*^2$ is the mean column density of the star and $M_8 \equiv M_\mathrm{BH}/10^8 M_\odot$. Beside the shrinking of the semi-major axis this interaction leads to circularization of the orbit and its decay into the plane of the disc (Karas & Šubr 2001). We distinguish two different modes of subsequent migration towards the center once the star gets embedded in the disc. If the star's Roche radius is larger than the half-thickness of the disc, it opens a permanent gap in it and follows its slow radial inflow. If the gap is not opened, the star excites density waves in the gas which leads to larger transfer of angular momentum and, consequently, faster inward migration (Lin & Papaloizou 1986; Ward 1986) on the time-scale of

$$t_\mathrm{drag} \approx 100\, M_8^{1/10} \left(\frac{M_*}{M_\odot}\right)^{-1} \left(\frac{a}{R_\mathrm{g}}\right)^{1/2} \mathrm{yr}\,. \tag{9}$$

The inner region of the star cluster interacting with the accretion disc is assumed to be continuously supplied with new stars on the relaxation time-scale:

$$t_\mathrm{relax} \approx 10^8\, n_6^{-1} M_8^{7/8} \left(\frac{M_*}{M_\odot}\right)^{-2} \left(\frac{r}{R_\mathrm{g}}\right)^{1/4} \mathrm{yr}\,, \tag{10}$$

where $n_6 \equiv n_0/(10^6 \mathrm{pc}^{-2})$ is the stellar density. Condition $t_\mathrm{coll} < t_\mathrm{relax}$ defines radius R_out of the region which will be emptied due to the drag imposed by the disc upon the stars. The inflow rate of stars towards the center through the boundary of this region is (Šubr et al. 2004)

$$\dot{N} \approx 10^{-2}\, n_6^2\, M_8^{5/4} \left(\frac{M_*}{M_\odot}\right)^2 \frac{R_\mathrm{out}}{10^4 R_\mathrm{g}}\, \mathrm{yr}^{-1}\,. \tag{11}$$

4. The Galactic center

The closest galactic nucleus is that of the Milky Way. It harbors a SMBH of mass $M_\mathrm{BH} \approx 3.5 \times 10^6 M_\odot$ (Genzel et al. 2003; Ghez et al. 2003) which manifests itself as a radio source SgrA*. In spite of that current activity of SgrA*is highly sub-Eddington, there is an indirect evidence for an existence of massive accretion disc few million years ago: The near infrared observations of the central parsec have revealed a numerous population of young stars. Moreover, it has been found (Levin & Beloborodov 2003) that considerable fraction of them forms a relatively thin disc rotating coherently around the SMBH. Fragmentation of a self-gravitating gaseous disc of mass $\gtrsim 10^4 M_\odot$ is currently one of the most popular explanation of the origin of this young stellar structure.

Stellar disc induces axisymmetric perturbation to the potential of the SMBH. Therefore, we assume that it leads to the eccentricity oscillations of late-type stars from the embedding spherical stellar cusp. In

Karas & Šubr (2007) we have estimated that up to 100 stars (i.e. $\sim 2\%$ of the stars from the region with $r \lesssim 0.3$pc may have been tidally disrupted due to this process within the lifetime of the disc. Another source of axisymmetric perturbation to the gravity of the central black hole is a circum-nuclear disc (CND), a molecular torus of mass $\gtrsim 0.1 M_{\rm BH}$ and radius ≈ 1.6pc. In spite of its larger mass compared to the stellar disc, the CND is relatively less effective in pushing the stars to extreme eccentricities due to its larger radius. Smaller efficiency is, on the other hand, balanced by larger number of stars that are influenced. Hence, another ~ 100 stars from the region below 1.5pc may have been tidally disrupted due to the gravity of the CND.

5. Conclusions

Gas in the galactic nuclei can manifest itself not only by means of its own radiation. It forms complex environment together with the supermassive black hole and millions of stars. All these components mutually interact and influence themselves. In this contribution we have focused on the effects of the gravitational and hydrodynamical influence of the gas in the form of accretion disc or torus upon the stars. We have discussed the effect of Kozai oscillations and shown that they are likely to lead to enhanced rate of tidal stellar disruptions. Due to the relativistic pericenter advance, this process is strongly damped for $M_{\rm BH} \gtrsim 10^7 M_{\odot}$, while it is the most efficient for intermediate masses of the black holes, i.e. it can help them to grow from the IMBH to the SMBH stage.

Passages of the stars through the gas dissipate their kinetic energy. This leads to their continuous inflow towards the black hole. The mass flow in the form of stars has to be small, compared to the accretion rate of the gas, otherwise, the gaseous structure would be destroyed. The individual stars may, however, be detectable in the final phase of their inspiral due to the emission of gravitational waves.

Recent observations of the Galactic Center indicate recent star formation at a distance of $10^5 - 10^6 R_{\rm g}$ from the SMBH. This goes in line with previous theoretical considerations about fragmentation of the outer parts of the accretion discs due to self-gravity (Collin & Zahn 1999). In addition, recent numerical simulations of the fragmenting accretion flow suggest that star formation may inhibit further inflow of the gas onto the central mass (Nayakshin et al. 2007). Hence, the feedback from stars should be considered in realistic models of AGNs.

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